AN AUGMENTED REALITY SIMULATED STERILE ENVIRONMENT FOR ASEPTIC TECHNIQUE TRAINING

by

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Declaration of Originality

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Statement of Ethical Conduct

The research associated with this thesis abides by the international and Australian codes on human and animal experimentation, the guidelines by the Australian Government's Office of the Gene Technology Regulator and the rulings of the Safety, Ethics and Institutional Biosafety Committees of the University.

Ethical approval for the research was gained from the Tasmania Social Sciences Human Research Ethics Committee for the preliminary investigation in 2009 and for the evaluation study in 2012 – Ethics Approval Numbers H10807 and H0012934 respectively. The preliminary investigation's observational study of undergraduate nursing students also had permission from the Head of School, School of Nursing and Midwifery, University of Tasmania.

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Abstract

Hospital Acquired Infections (HAIs) are a leading cause of death worldwide. In the United States, the death toll from HAIs exceeds that of AIDS, breast cancer, and motor vehicle accidents combined, totalling nearly 100,000 deaths annually. The correct application of aseptic technique by healthcare professionals is critical to the reduction of HAIs. However, the intricacies of maintaining a sterile field can be difficult for students to grasp due to the invisible nature of pathogens. Traditional teaching methods provide limited opportunity for students to receive feedback on their technique from qualified staff. Clinical settings also afford minimal feedback due to the delay between breaches of asepsis and occurrence of infection.

This research presents a novel approach to aseptic technique training that utilises Augmented Reality (AR) technology to simulate a sterile environment. A prototype system, *ARSterileSim*, was developed based on the findings of a preliminary exploratory study. ARSterileSim tracks the movements of a user as they attempt a basic wound dressing procedure, providing feedback via colour-coding on a virtual mirror and auditory cues. The system makes the invisible visible, alerting the user when contamination occurs thereby completing the feedback loop.

Face and content validity of the ARSterileSim prototype was assessed via a mixed methods triangulation study involving interviews with ten experts in aseptic technique training, from both academic and clinical backgrounds.

Results indicate that while the prototype's markers and tracking accuracy require improvement, the approach in general has face validity. The findings also provide evidence of content validity within the defined scope of the prototype, which excluded hand tracking. Participants placed particular value on the visual and auditory real-time feedback, as well as the fact that learning takes place in a tangible context, enabling strong transfer of learning to clinical practice. Further work in this area is therefore recommended.

Acknowledgements

I could not have completed this thesis without the support of many others over the past several years.

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Thank you so much, my beautiful wife, Kylie, for all the love and support you've given me, particularly while undertaking this degree, which has so far been going longer than our marriage. I look forward to our coming thesis-free life together! I love you so very much.

Finally thanks be to God, who began a good work in me and will carry it on to completion until the day of Christ Jesus.

Table of Contents

List of Tables

List of Figures

1 Introduction

Hospital Acquired Infections (HAIs) are infections introduced to a patient during a hospital stay. While some infections are readily dealt with through the use of antimicrobial drugs, many infection-causing pathogens are becoming increasingly resistant to treatment. Anti-microbial resistance (AMR) is a growing global concern, and reduction of HAIs are a key factor in reducing AMR. It has been shown that 38% of HAIs are wound related and could be prevented by appropriate aseptic technique (Ford & Koehler 2001; Welsh et al. 2012). It is therefore imperative that healthcare workers are adequately trained in maintaining a sterile environment when working with wounds.

However, medical or nursing students practising aseptic technique have no reliable way to identify that they have made an error unless they are being observed by an expert. It is impractical to have sufficient experts available at all times to provide feedback to a large number of students in the classroom. Thus, errors often go unnoticed by students, which can result in the learning of incorrect technique.

Professional healthcare workers also lack feedback on their aseptic technique in clinical practice due to the delay between breaches and occurrence of infection. Studies have shown that aseptic practice varies considerably among healthcare workers, and unlike most other skills, aseptic technique does not improve with experience (Friedman, Siddiqui & Katznelson 2008; Labrague et al. 2012).

Augmented Reality (AR) is a technology that seamlessly blends computer generated 3D content with the real world, often through the use of a Head Mounted Display (HMD). For example, Figure 1.1 shows a virtual character standing on a physical platform. AR has many potential applications in many fields including medicine, e.g. augmenting a surgeon's view of a patient with an image of a tumour in the precise actual location of that tumour; and education, e.g. augmenting a view of a historic landmark with a virtual reconstruction of what it looked like 50 year ago.

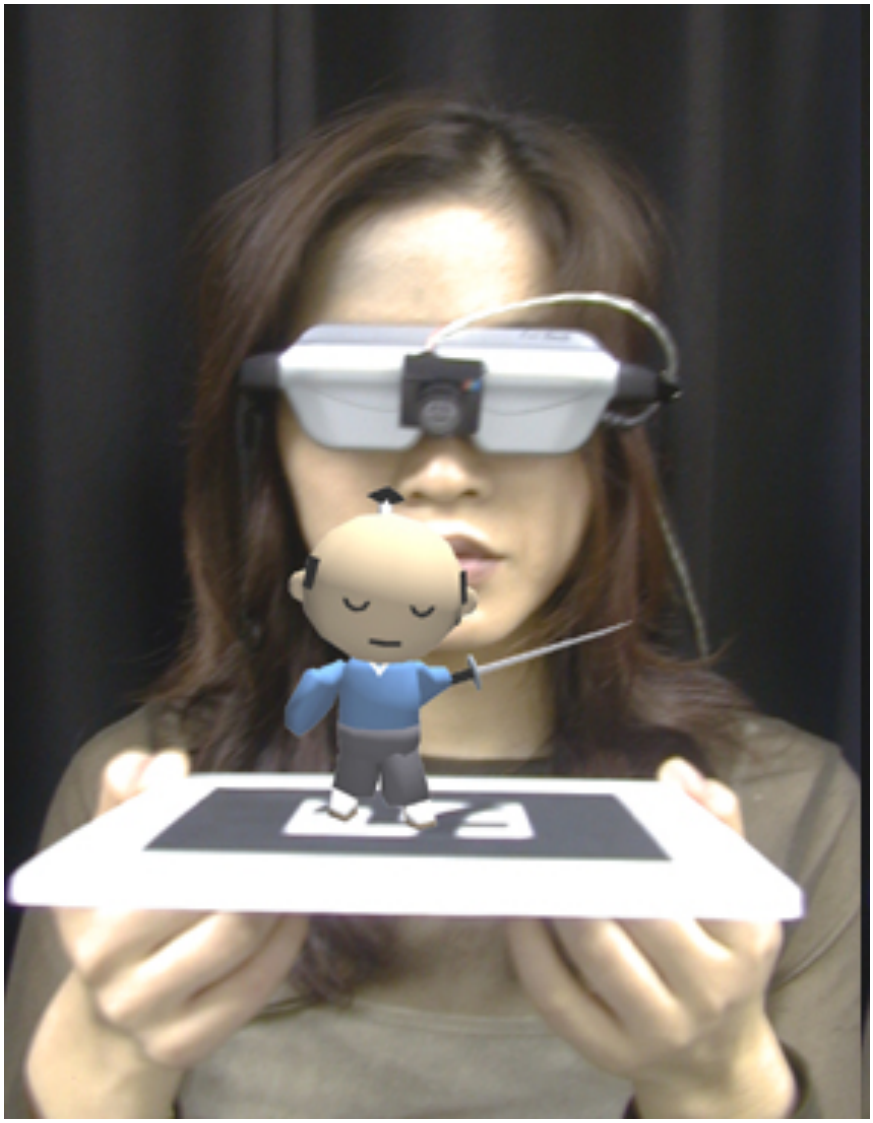


Figure 1.1: Augmented Reality technology adds virtual imagery to real world objects (HITLab 2006)

This research presents a novel approach to aseptic technique training utilising AR technology to simulate a sterile environment, colour-coding sterile and non-sterile objects so the user can build a mental model of what actions cause contamination. A prototype system, *ARSterileSim*, is described and tested for face and content validity. Video and audio feedback is delivered in real-time to users as they practise aseptic technique, completing the experiential learning cycle and promoting a deeper understanding. The final ARSterileSim prototype is pictured in Figure 1.2.

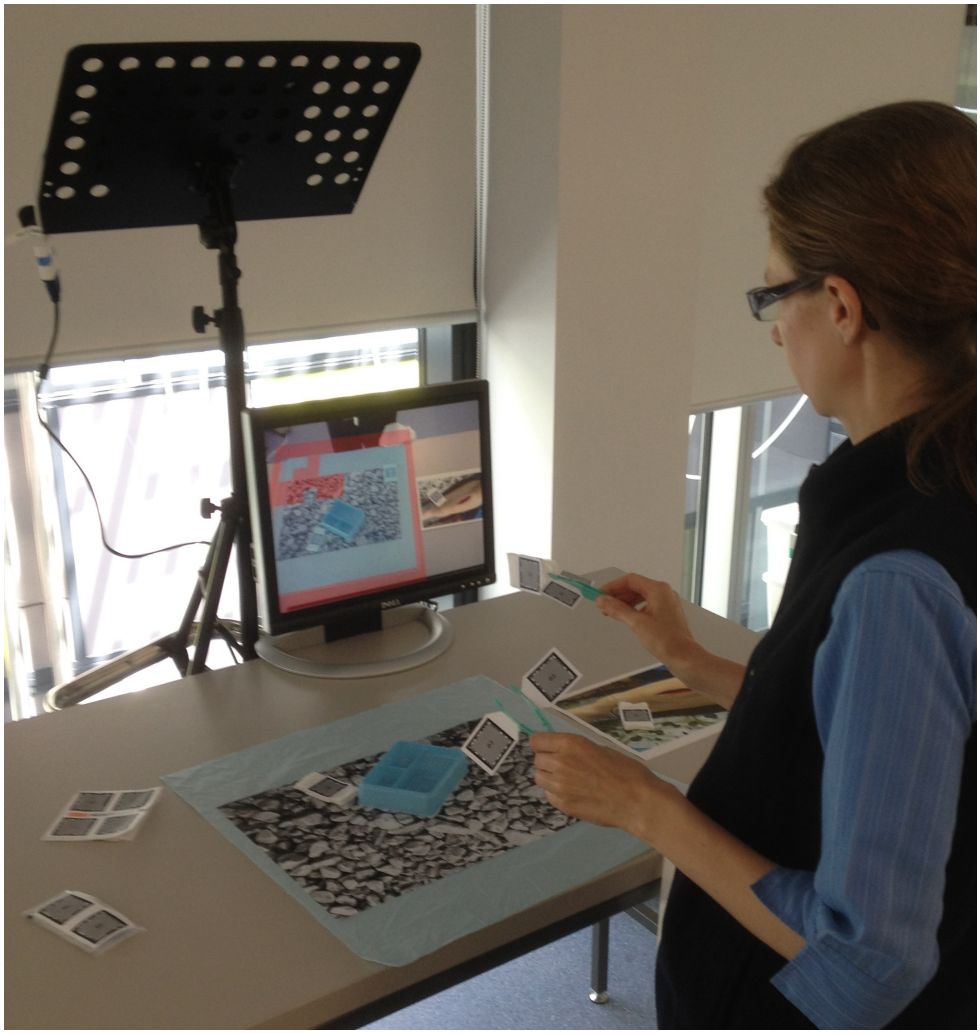


Figure 1.2: The final ARSterileSim prototype being used by a healthcare worker.

1.1 Purpose of the Research

The research seeks to establish a rationale for using Augmented Reality in aseptic technique training as well as to identify design guidelines that can be used to develop an Augmented Reality aseptic technique training simulator.

1.2 Research Design

A preliminary study will first be undertaken to establish appropriate requirements for the prototype system's design. This will be followed by an evaluation study, which aims to provide an assessment of the face and content validity of the ARSterileSim prototype system, employing an interviewer-administered questionnaire. This research employs a mixed methods ap-

proach, combining the strengths of qualitative and quantitative methods to best understand the research problem.

1.3 Thesis Structure

First, a review of the literature covering topics from healthcare, simulation, augmented reality, and relevant research methods will be presented in Chapter 2. Chapter 3 discusses the preliminary investigation's methodology and findings. The results of which informed the design of the ARSterileSim prototype system, which is presented in Chapter 4. Chapter 5 covers the evaluation study of the prototype. Finally, conclusions are drawn in Chapter 6, including recommendations for further work.

1.4 Contributions of the Thesis

This research aims to provide an underpinning for further work in Augmented Reality aseptic technique training simulators by establishing the face validity of the approach and the content validity of a working prototype. This appears to be a novel approach that has not been investigated previously. Design factors are also discussed which provides guidelines and suggestions for a future iteration of the simulator.

2 Literature Review

The literature that was reviewed in relation to this study covers a number of fields. First, hospital acquired infections (HAIs) are examined to establish the motivation for this work, along with the shortcomings of existing teaching methods. This is followed by a discussion of the use of Simulation as a teaching technique in the field of healthcare. Augmented Reality technology is then discussed in terms of its suitability to this application domain. Finally, a review of research methods is undertaken focussing on mixed methods.

2.1 Healthcare Background

This section presents an examination of the literature related to the research problem. HAIs and aseptic technique will be covered, as well as the educational technique of simulation and issues surrounding the validation of simulators.

2.1.1 Hospital Acquired Infections (HAIs)

A hospital acquired infection (HAI) (also known as a healthcare-associated infection, or a nosocomial infection) is an infection occurring in patients after admission to hospital that was neither present nor incubating at the time of admission (Aziz 2009). The incidence rate of HAIs has risen over the past decade, and antimicrobial drugs hitherto relied on to treat HAIs are becoming increasingly ineffective due to growing antimicrobial resistance (AMR) (Collignon, Nimmo & Gottlieb 2005; Pollack 2010; Welsh et al. 2012). The World Health Organization (2012) has long recognised AMR as a growing global health threat, and identify HAIs as a critical component of the AMR problem (World Health Organization 2001). Prevention of HAIs is therefore paramount.

In the United States, HAIs are estimated to affect approximately 1.7 million persons and cause nearly 100,000 deaths each year, surpassing AIDS, breast cancer, and automobile accidents combined. HAIs are also responsible for increasing the cost of health care by $17–20 billion due to additional treatment and extended hospital stays (Welsh et al. 2012). In Europe current estimates exceed 25,000 deaths per year (World Health Organization 2012), while in

Great Britain alone, 2009 estimates placed hospital acquired infections at 300,000 per year and deaths at around 9,000 per year at an estimated annual cost of £1 billion. The British Government considers the reduction of HAIs a top priority for the National Health Service (National Audit Office 2009).

Two of the primary factors influencing the incidence rate of HAIs are hand hygiene practice (Stone et al. 2012) and aseptic technique (Lewis 2009; World Health Organization 2001). Hospitals that have focussed on practical training in these areas along with running campaigns to raise awareness of these issues have seen improvements in infection rates (Aziz 2009; Stone et al. 2012). This research focuses on aseptic technique, leaving hand hygiene to others.

2.1.2 Aseptic Technique

The aim of aseptic technique is to prevent the transmission of microorganisms to wounds or other susceptible sites, to reduce the risk of infection (Preston 2005). To achieve this, only sterile objects and/or fluids must be allowed to come in contact with the wound (Bree-Williams & Waterman 1996). Practically this involves knowing what is sterile, knowing what is not sterile, minimising contact between two, and correcting for any breaches that occur during the procedure (Gillespie & Fenwick 2009).

Although this sounds straightforward, there remains confusion among healthcare workers surrounding specific aseptic technique practises due to widely varying policies between different healthcare facilities, or even different procedures within a single facility. For example, Bree-Williams & Waterman (1996) noted that the transfer technique (also known as “clean/dirty” technique) was not used in London and the southeast of England but was used in the northwest. This forces educational institutions to teach multiple procedures, complicating matters. Rather than contending with a variety of approaches to aseptic technique, healthcare workers should internalise the theory underpinning these practices and be encouraged to adopt a single unified approach (Aziz 2009; Unsworth 2011).

Lack of Feedback

Because microorganisms are invisible to the naked eye, it is impossible to see when the sterile field has become contaminated. In a study of epidural anaesthesia administration skills, Friedman et al. (2008) found that while technical skill correlated with number of epidurals performed, aseptic technique did not. The authors suggested that this could be due to the inherent feedback (tactile and other) present when employing technical skills, whereas no similar feedback exists for sterility. Additionally, aseptic technique is always a sec-

ondary goal with respect to the technical skill being undertaken, so it may not receive the same level of scrutiny from practitioners.

Similarly, Labrague et al. (2012) found that length of clinical experience is not a predictor of aseptic technique. They also reported, however, that there is a clear association between knowledge and extent of practice of aseptic technique. This, together with other research, suggests that to see improvement in aseptic technique, educational efforts should focus their attention on teaching underlying theory rather than trying to enforce compliance with a step-by-step procedure (Lewis 2009). As explained by Gillespie & Fenwick (2009):

> *Using a framework based on principles rather than relying on a set of prescriptive steps to perform wound dressings will enable nurses to better understand the consequences of their actions and thus contribute to reducing the risk of HAIs.*

Not only is contamination itself invisible, but any infections caused by breaches are not evident until days later, making tracing the source of an infection difficult or, in some situations, impossible. As the National Audit Office (2009) reports:

> *Given the delay between failure to comply and infection, some staff still do not see a clear link between their actions and healthcare associated infection.*

Preston (2005) sums up these issues thus:

> *...one of the reasons for non-compliance in the aseptic technique is because the individual cannot see the microorganisms with the naked eye. The relationship between contamination, colonization and infection is not easy for the average professional to perceive in practice, and it can take many days for an infection to develop.*

Educational strategies employed to attempt to overcome the invisible nature of microorganisms include the use of dyes, gels, powders, or even colourful pom-poms with parachutes to represent the spread of microbes (Preston 2005).

One popular product called Glo Germ (2012) is a material that is invisible under normal lighting conditions but glows when exposed to Ultra-Violet (UV) light. Glo Germ is ideal for training correct hand washing technique: participants apply Glo Germ to their hands, attempt to wash them thoroughly, then check under a UV light for areas they have missed. There is also potential for Glo Germ to be used for aseptic technique and other applications.

These physical aids provide a visible representation of invisible processes that occur during the practice of aseptic technique. Visualising the spread of germs using these techniques is effective in improving healthcare worker awareness regarding the importance of strict aseptic technique (Ford & Koehler 2001; Preston 2005), however each have limitations: pom poms are useful as a visual aid in demonstrating to a group how contamination spreads, but is not a hands-on solution. Dyes, gels, and powders require single-use setup, which is prohibitively time-consuming for complex tasks, as well as being a potentially expensive consumable, especially where repetition is required. Glo Germ lacks instant feedback, and resetting sterile objects would essentially require replacing them.

Aseptic Conscience

An alternative focus to that of teaching students any particular technique is one of developing students' *aseptic conscience*. Lewis (2009) defines an aseptic conscience as:

> *The awareness of sterile and non-sterile items contained within a wound field and the ability to take corrective action should contamination occur, underpinned by the ethic that nurses should do the patient no harm.*

Aseptic conscience is difficult for students to internalise through traditional didactic teaching methods. Instead, students should be encouraged to engage in practical experience, with appropriate feedback, to gain the necessary cognitive and psychomotor skills.

2.2 Simulation in Healthcare

Simulation is an educational technique that allows participants to gain experience in an interactive, and at times immersive, activity by recreating all or part of a clinical experience without exposing patients to the associated risks (Maran & Glavin 2003).

Simulation is relevant not only at undergraduate level, but is also of growing importance for continuing training of experienced personnel. The aviation industry has for some time required pilots to regularly spend time in flight simulators in order to maintain their certification. Simulation is well-established practice in a number of other high-risk industries, such as aviation, nuclear power production, and the military, and is gaining traction in the healthcare industry (Gaba 2004).

There are a several classes of healthcare simulator, including Part-Task Trainers, Simulated Patients and Environments, Integrated or High-Fidelity Simulators and computer-based systems (Bradley 2006).

Part-Task Trainers provide a model of only part of the simulated construct for the purpose of acquiring a specific technical, procedural or psychomotor skill. For example, a part-task trainer might be used as a wound management teaching aid for learning the skill of suturing (Figure 2.1).

A simulated patient can be an actor trained to present a history and sometimes to mimic physical symptoms of a condition, or a computer-simulated virtual character that can be interacted with via some interface. Figure 2.2 shows an example of a simulated patient made up of a virtual computer-generated character, coupled with a tangible haptic interface for the purpose of simulating a breast examination. In this case the virtual character allows training of interpersonal skills whilst undertaking a sensitive examination, while the haptic interface provides training of the technical skill itself.

Fidelity is a general measure of the level of detail or comprehensiveness of a simulation. However, the terms 'high-fidelity' and/or 'integrated' generally refer to a sophisticated mannequin in the context of a realistic simulated clinical environment (such as a hospital operating or ward room) with integrated simulated monitoring and intervention devices, all controlled by instructors typically in a control room. High fidelity mannequins such as SimMan by Laerdal simulate pulse and heart rhythms, can be programmed with a wide range of scenarios but also react automatically to the administration of certain drugs and therapeutic interventions. SimMan is pictured in Figure 2.3 and the control room in Figure 2.4. High fidelity simulation is not necessary or even appropriate for some technical skills training, but is highly valuable for providing experience in diagnosing and treating a wide range of conditions and dealing with unexpected complications (Maran & Glavin 2003).

Computer-based systems are generally training tools presented through a computer screen interface and are often focussed on content that is procedural in nature. More advanced systems can include haptic and virtual reality elements.

Whilst some simulation experiences have great potential for learning in and of themselves, specific feedback as to the performance of the participant is of much added educational value (Gaba 2004). In fact, in a systematic review of studies into high-fidelity medical simulators, feedback was identified as the single most important feature of a simulation in terms of effective learning (Issenberg et al. 2005).

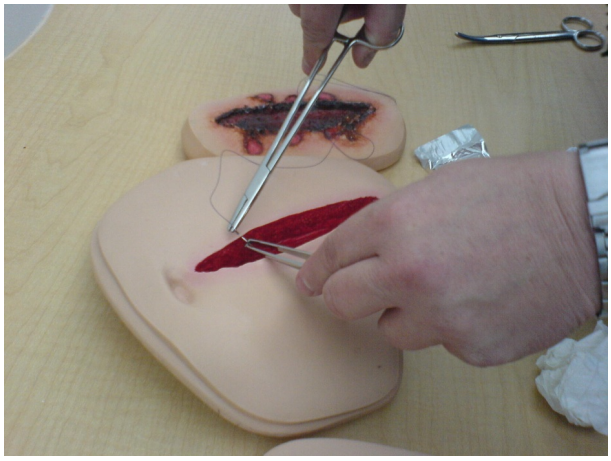


Figure 2.1: Wound Part-Task Trainer Simulator, being used for suturing (made by Laerdal, photo taken at School of Nursing and Midwifery, UTas)

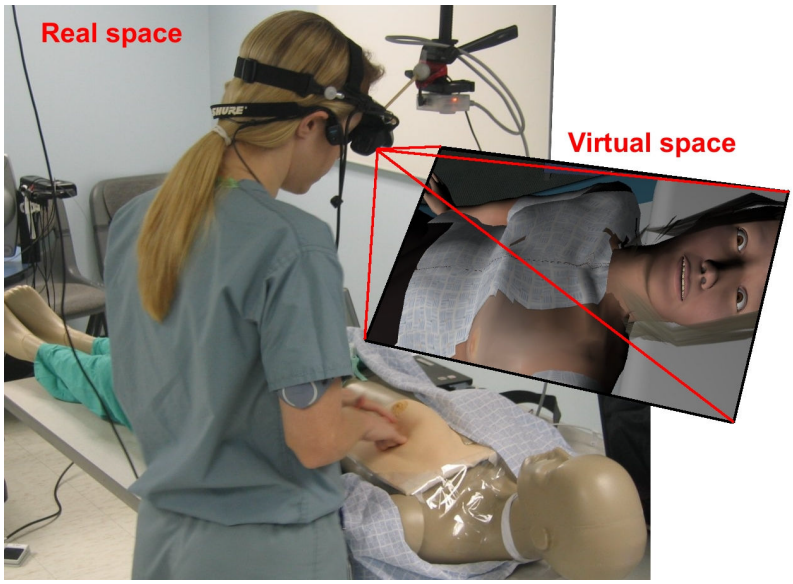


Figure 2.2: Mixed Reality Virtual Breast Exam Patient – Virtual Human + Tangible Interface (Kotranza & Lok 2008)

Underpinning Simulation is the concept of "learning by doing" or "experiential learning" also referred to as constructivism. Kolb (1984) described a learning cycle, illustrated in Figure 2.5, containing four steps: concrete experience, reflective observation, abstract conceptualisation, and active experimentation. It is through experiencing some construct, reflecting on what is observed, formulating a hypothesis to explain what was observed, then testing that hypothesis through active experimentation that results in learning. Simulation allows this process to occur in a safe environment.

Figure 2.3: SimMan High Fidelity Integrated Simulation (Laerdal 2013)

Figure 2.4: SimMan – view from control room (Laerdal 2013)

It should be emphasised that this concept is build on the premise that the results of actions can be observed. In the absence of feedback, the cycle is broken and learning fails to take place.

Windschitl & Winn (2000) used a virtual reality based simulation to provide a visualisation of a construct that is normally invisible to the observer. The subject matter was the ecology of a water system. The simulation used metaphor, such as colour and arrows, to represent key constructs, such as salinity and water flow, and promoted active experimentation by allowing certain variables to be altered. Providing a means to observe phenomena allowed users to explore the topic and construct knowledge about it. While results showed measurable gains in conceptual understanding of water phenomena, some participants misinterpreted the meaning of some metaphors, resulting in

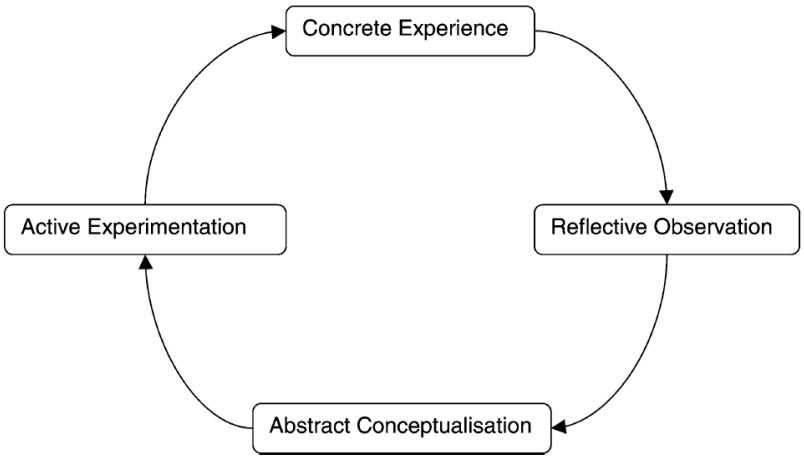


Figure 2.5: The experiential learning cycle (Kolb 1984)

faulty mental models. It is therefore critical that any simulator undergo testing to ensure it represents a valid model.

2.2.1 Simulator Validity

Before any simulator should be used in an educational context it is imperative that its validity be assessed (Carter et al. 2005; Iwata et al. 2011). Schreuder et al. (2009) define validity as "the property of being true, correct, and in conformity with reality." There are several levels of validity to be attained, each providing more powerful evidence that the simulator true and correct. Of particular importance and relevance are face, content, construct, and concurrent (or predictive) validity.

Face validity

Face validity measures the extent to which a user judges the simulator to resemble the construct being simulated (Schreuder et al. 2009). That is, does the simulation appear to be valid to an average user *at face value?* Face validity is the most basic level of validity and is commonly established prior to measuring other types of validity (Gavazzi et al. 2011; Sánchez-Peralta et al. 2010; Stefanidis et al. 2007).

Face validity is also important in terms of user acceptance; if the simulator does not appear to be valid, users will not readily accept what the simulator is trying to teach them.

Content validity

Content validity is an assessment of whether the simulator covers the breadth of skills fundamental to the simulation (Fried 2006). Like face validity, content validity is a largely subjective measure, however expert opinions are utilised in place of average users. Assessment is typically achieved by virtue of a questionnaire using Likert scales (Gavazzi et al. 2011).

Construct validity

Construct validity measures the degree to which the simulator can discriminate between different ability or experience levels (Carter et al. 2005; Rosenthal et al. 2007). In other words, construct validity asks the question: "do users with superior skills perform better in the simulator?" Construct validity is typically measured by comparing the simulator's assessment of participant skill level with a traditional assessment or known experience level (Schreuder et al. 2009).

Concurrent (or predictive) validity

The most powerful indication that a simulator will be effective for learning is evidence of concurrent or predictive validity. This type of validity measures whether performance in the simulator transfers to (predicts) performance in clinical practice (Carter et al. 2005). It asks the question, "Is the user becoming an expert at the task being simulated, or merely an expert at using the simulator?"

Concurrent validity can be assessed by measuring participant performance using previously validated tests pre- and post- simulator training, usually in a randomised controlled trial (Sturm et al. 2008).

2.2.2 Effectiveness for Learning

Overall, the literature agrees that simulation in healthcare is at least as educationally effective as alternative training methods (Sturm et al. 2008). Furthermore many studies of simulator concurrent validity have shown experience with the simulator to improve speed and accuracy, and reduce errors and risk of complications (Aggarwal et al. 2007; Grantcharov et al. 2004; Seymour et al. 2002; Sturm et al. 2008).

Sutherland et al. (2006) observes that many studies measure construct validity and not concurrent validity. While concurrent validity is the ultimate goal for proving the educational effectiveness of a simulator, each level of validation builds on the last and each is a useful step in this process.

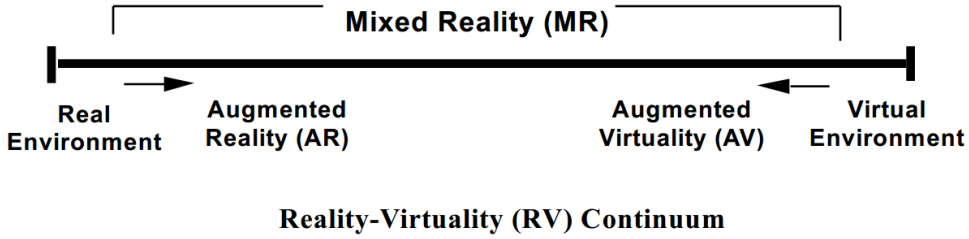


Figure 2.6: Milgram's Reality-Virtuality Continuum (Milgram & Takemura 1994)

2.3 Augmented Reality (AR)

Augmented reality (AR) is a technology in which the display of computer generated content is overlaid on a view of real world objects in real time. The virtual content is registered with the real world in 3-dimensional space, so that the virtual and the real appear blended together seamlessly (Zhou, Duh & Billinghurst 2008).

AR can also be defined in terms of its position on the Reality-Virtuality (RV) Continuum as defined by Milgram & Takemura (1994), shown in Figure 2.6. The RV Continuum places real environments and purely virtual environments at opposite ends of the spectrum, with everything in between falling under the generic "Mixed Reality" label, in which real and virtual elements are presented together in a unified view. Augmented Reality is therefore a Mixed Reality environment that includes more real elements than virtual. An environment that is predominantly virtual with some real elements is referred to as Augmented Virtuality. An all virtual experience is known as Virtual Reality.

2.3.1 Marker and Markerless Tracking Technology

An AR system must accurately track the position of real objects in three dimensions in order to overlay seamlessly blended virtual content. This tracking is typically achieved using vision-based feature recognition techniques. Image processing methods are used to identify known features on real world objects from which relative camera pose can be estimated. Early work in AR made extensive use of fiducial markers designed to be easily recognisable by AR systems, however a trend towards Natural Feature Tracking (NFT), a technique that utilises visual features that occur naturally in a scene, has been observed over the last decade (Zhou, Duh & Billinghurst 2008).

Fiducial Markers

Fiducial markers have predefined features that the corresponding AR tracking algorithms look for in order to recognise a marker from other objects in a scene, identify one marker from another, and estimate relative camera pose. An example of a fiducial marker can be seen in Figure 2.7. In this case a black boundary provides a clearly defined edge for pose estimation, and black and white blocks along the interior edge are arranged in a pattern that uniquely identifies the marker from a set of 512. In this particular example the area inside the marker (orange) is ignored by the tracking algorithm and is therefore available to carry any design.

Natural Features Tracking (NFT)

NFT algorithms are designed to track objects in their environment by utilising naturally occurring features in a scene. Features can be acquired dynamically as the tracking runs, adapting to whatever environment is discovered, or tracking targets can be pre-defined. Figure 2.8 shows an example of a pre-defined tracking target that has been analysed for trackable features, indicated by yellow crosshairs. This image has been specifically designed to be an ideal candidate for natural feature tracking by virtue of featuring plenty of high-contrast non-repeating bold detail. Truly naturally occurring features are typically less ideal.

Active Infrared Depth Sensors

An alternative to the purely vision-based approach to AR tracking that has recently gained momentum is the use of active infrared depth sensors. This approach has been popularised by Microsoft's Kinect sensor, pictured in Figure 2.9. Kinect projects infrared laser light in a speckle pattern into the environment then observes the displacement via an offset camera. This data allows a depth-map to be produced, an example of which can be seen in Figure 2.10.

A depth-map allows objects to be more easily extracted from the background and can also be combined with vision-based tracking algorithms via a calibrated conventional camera.

Figure 2.7: An example of a fiducial marker (a "frame marker") used in Qualcomm's Vuforia AR SDK (Qualcomm 2012)

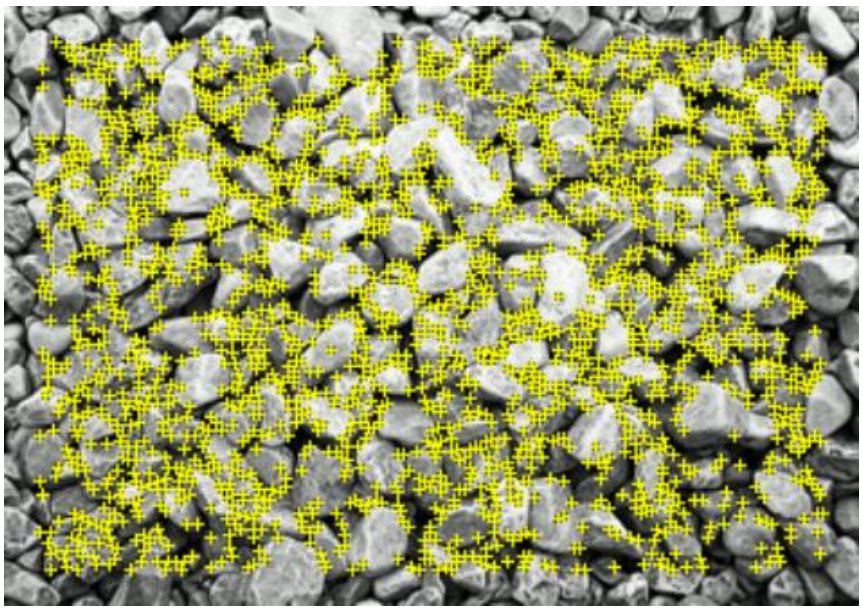


Figure 2.8: "Stones" – an Image Target utilising Natural Feature Tracking with detected features identified (Qualcomm 2012)

2.3.2 Marker and Markerless Tracking Challenges

Vision-based AR tracking is susceptible to a number of confounding factors. Lighting is ideally moderate (not too dark or too bright) and ambient (to minimise reflections). Camera and image processing resolution needs to be high enough to distinguish features, but higher resolutions require more processing power, potentially increasing latency.

Fiducial markers require a high percentage of a marker to be visible for reliable tracking. NFT algorithms only require a certain number of features to be recognised in order to maintain tracking so are more robust to partial occlu-

Figure 2.9: Microsoft's Kinect Sensor (Microsoft 2013)

Figure 2.10: Depth map from a Kinect Sensor represented in greyscale (Wilson et al. 2012)

sion. A similar effect can be achieved with marker-based AR by arranging multiple markers into a predetermined pattern, such that any one marker reveals the relative locations of the others in the set.

Tracking targets oriented at too steep an angle with respect to the camera plane can also become difficult to track, depending on relative marker size and camera resolution. Motion blur due to fast movements and shutter speeds that are unable to keep up also present tracking challenges.

Despite the best efforts of tracking algorithms, there comes a point where tracking is unable to be maintained. If tracking algorithms are too eager to detect markers or NFT features, false positive detection can occur, where some

other object in the scene is mistakenly recognised as a marker or feature (Fiala 2004; Uematsu & Saito 2008).

These issues and others must be considered when designing a vision-based augmented reality tracking system. With appropriate design choices for any given application, these limitations can be mitigated.

2.3.3 AR Display Techniques

Augmented Reality is displayed to users by generating an image somewhere along the optical path between the observer's eyes and the physical object to be augmented (Bimber & Raskar 2005). The optical path and possible locations augmentations can be displayed are illustrated in Figure 2.11. As shown, these locations can be divided into three categories: head-attached, handheld, and spatial. Each approach has strengths and weaknesses and should be chosen according to the needs of the specific application.

Head-attached displays

Head attached displays are display devices that are worn on the user's head, providing augmentations that move as the observer moves. There are three main types of head-attached display: Retinal displays use low powered lasers to project an image directly onto the retina, head mounted displays (HMDs) form an image in front of the eye, and head mounted projectors project an image in front of the user onto the scene directly.

Head mounted displays must provide a see-through view of the real world that virtual imagery can be added to. There are two classes of see-through HMDs: optical see-through and video see-through. The two approaches are illustrated in Figure 2.12.

Optical see-through HMDs use half-silvered mirrors ("combiners" or "beam splitters") or similar to combine a direct view of the real world with virtual images. This has the advantage of a superior view of the real world, unhindered by latency, imperfect stereoscopy or field-of-view limitations. Augmentations may suffer from latency and registration accuracy difficulties however, affecting the perceived seamlessness between the real and the virtual.

The beam splitters, being partially transmissive and partially reflective, reduce the amount of light the user sees from the real world. Choosing an appropriate light balance between real and virtual is a key design problem for this type of display (Azuma & others 1997).

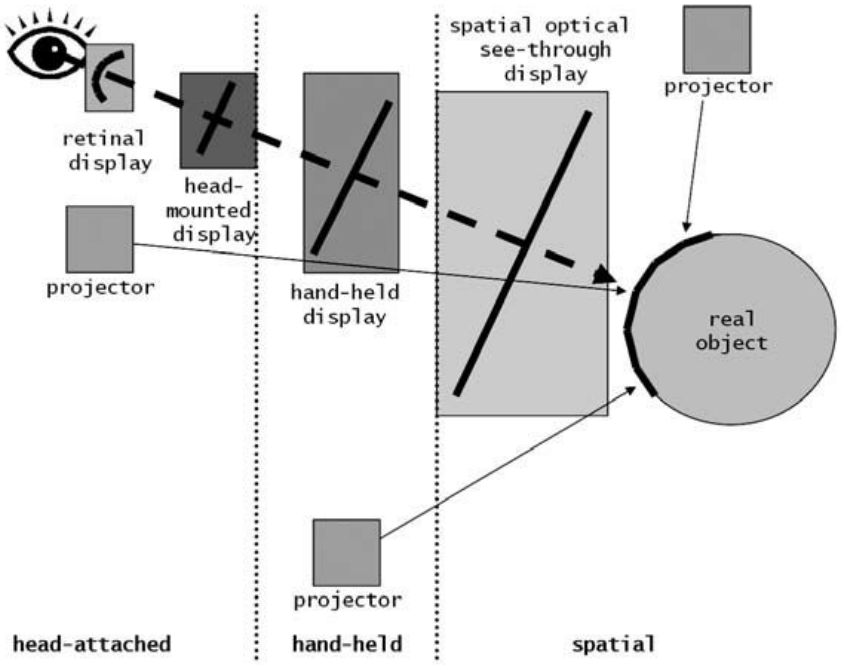


Figure 2.11: Image generation for augmented reality displays (Bimber & Raskar 2005)

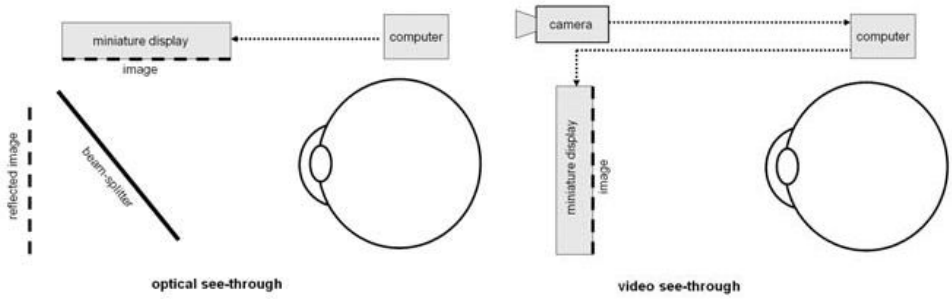


Figure 2.12: Optical vs Video see-through HMD (Bimber & Raskar 2005)

Video see-through HMDs utilise a video feed from one or two cameras attached to the front of the HMD, displaying this view to the user with augmentations added by video mixing. Advantages of this approach include better alignment and matched latency of virtual and real elements as well as real-time blending ratio control, enabling better occlusion management (Zhou, Duh & Billinghurst 2008; Rolland & Fuchs 2000). Disadvantages include a mediated view of the real world: resolution and latency are limited to that of the camera(s) and display hardware. Stereoscopy (if used at all) will be imperfectly matched to the user's unimpeded view due to the offset between the cameras and the user's eyes, introducing parallax error (Azuma & Baillot 2001). An example of a video see-through HMD is shown in Figure 2.13.

Figure 2.13: Video See-Through Head Mounted Display (Vuzix 2013)

Handheld displays

The proliferation of increasingly powerful smart phones and tablets has resulted in an abundance of AR applications for the handheld medium. Handheld displays typically utilise a video see-through display of the world usually via an integrated camera (although optical see-through handheld displays are also possible) (Bimber & Raskar 2006; Zhou, Duh & Billinghurst 2008).

Handheld displays provide a window or 'magic lens' style view of an object or scene but are not ideal for applications which involve significant manipulation of real world objects. This is due to the requirement that the device be positioned between the user and the object under scrutiny, and unless the device is mounted on a stand (making it a spatial display – see below) also leaves the user with at most one hand free to manipulate objects.

Figure 2.14 shows an Apple iPad being used as a hand-held display for augmenting a map of an estuary with a bar chart representing the ecological health of the estuary in various zones (NRM North 2013).

Spatial AR

Spatial AR detaches most of the technology from the user, instead integrating it into the environment. This can be accomplished via projectors that provide augmentations directly onto the surfaces of objects in a scene, or a fixed display screen that provides a virtual window into an augmented world. Spatial display AR typically does not require the user to wear or hold any equipment, allowing free movement and reducing barriers to engagement.

Figure 2.15 and Figure 2.16 provide two examples of projector-based AR. In the first example a virtual toy car drives around a room interacting with real-

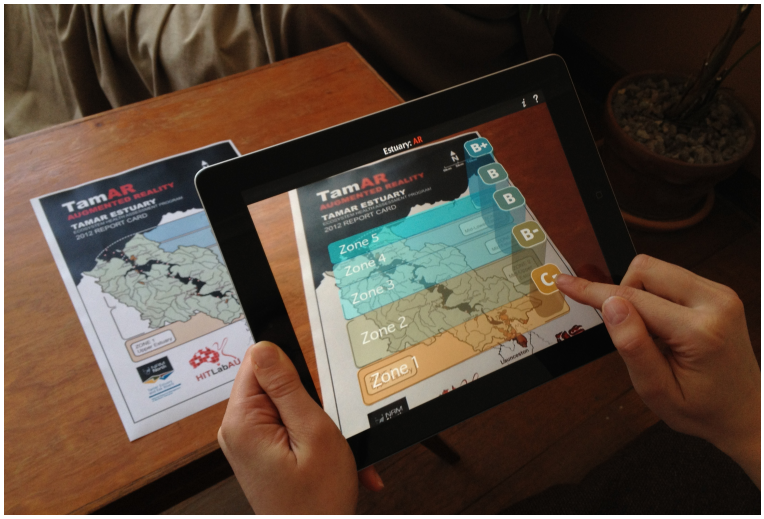


Figure 2.14: Hand-held display: TamAR Estuary Ecosystem Health Report Card iPad App (NRM North 2013)

world physical geometry such as ramps (mapped using a Kinect sensor) (Wilson et al. 2012). The second example depicts a laparoscopic surgeon being guided by an image of the patent's internal organs projected directly onto their abdomen (Sugimoto, Yasuda & Koda 2010).

Projectors provide an unhindered view of real objects and multiple projectors can be used to cover different points-of-view, focus points, or to provide stereoscopic 3D, typically in conjunction with polarized or shutter glasses.

Problems requiring consideration include interference from environmental lighting (generally requires controlled lighting conditions); non-planar projection surfaces which may require compensation in the rendering pipeline; and occlusions from real objects including the user(s) themselves. Additionally if tracking is being achieved visually, the projected augmentations can interfere with the tracking quality. As with optical see-through HMDs, projected AR systems can also present latency and registration accuracy challenges (Bimber & Raskar 2006).

Virtual Mirror Configuration

A virtual mirror is a specific configuration of spatial display that consists of a screen with a camera facing back towards the user. The screen displays a mirror image of the video feed from the camera resulting in a simulation of a mirror. Augmentations can then be added to the view, such as virtual clothes, shoes or jewellery (Eisert 2010; Eisert, Rurainsky & Fechteler 2007).

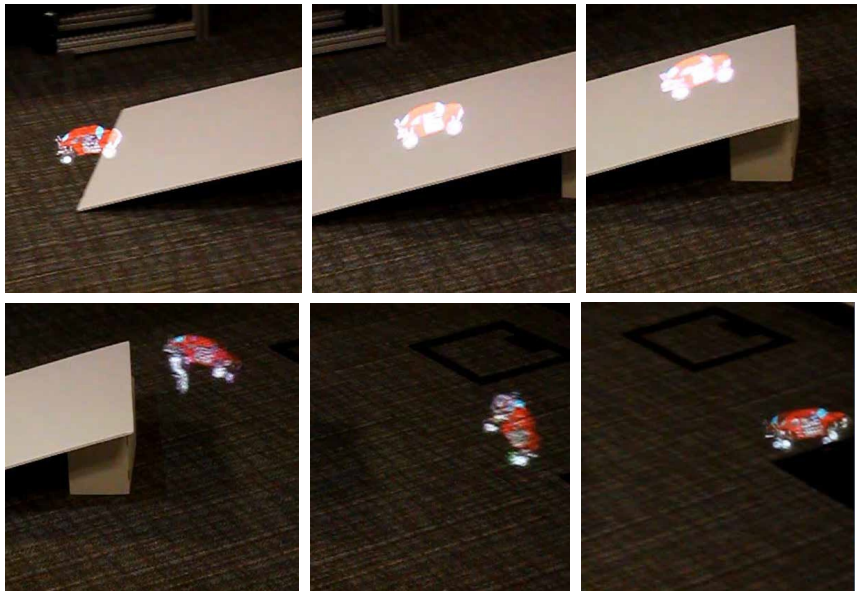


Figure 2.15: Projector-based AR: "Beamabuggy" virtual toy car interacting with physical room geometry (Wilson et al. 2012)

Figure 2.16: Projector-based AR: Prior scans of internal organs projected directly onto a patient's abdomen (Sugimoto, Yasuda & Koda 2010)

A virtual mirror does not require the user to wear or hold any special equipment and is a recognisable metaphor: everyone already knows how to use a mirror. Figure 2.17 shows a virtual mirror developed by Cisco deployed in a clothing store (Fretwell 2012).

Mirrors can sometimes cause orientation confusion regarding left/right directionality. A classic test requiring a user to trace an image whilst only looking through a mirror demonstrates this. Testing should therefore be done to en-

Figure 2.17: Virtual Mirror: Cisco StyleMe Virtual Fashion Mirror (Fretwell 2012)

sure that AR applications employing a virtual mirror metaphor employ a configuration that is intuitive and that users do not become disoriented using.

2.3.4 Tangible User Interfaces

So far in this section, AR tracking technologies and display techniques have been discussed. This covers the technology for making visual augmentations a reality, however the way in which users interact with such systems should also be considered.

Back in 1997, Ishii & Ullmer (1997) observed that AR systems to date were typically concerned with purely visual augmentations that were simply an overlay of digital information, with little or no interaction beyond the viewing of the overlaid content. Today this is still often the case, particularly in light of the current trend of handheld display-based AR that has arisen out of the prevalence of more powerful mobile devices. These handheld display-based AR applications often use a single marker as a point of reference, but any interaction in accomplished via the device's touch screen in traditional GUI fashion (e.g. Figure 2.14). Ishii & Ullmer proposed an approach to AR interaction that utilised the tangible nature of real-world objects and established the field of Tangible User Interfaces (TUI).

TUI allows interaction with virtual constructs by manipulating physical objects. To quote Kato et al. (2000):

> *The goal of Tangible User Interface research is to turn real objects into input and output devices for computer interfaces.*

Although TUIs certainly do not have to use AR technology, they are clearly complementary. Billinghurst, Kato & Poupyrev (2008) describe it thus:

> *Tangible AR interfaces combine the enhanced display possibilities of AR with the intuitive manipulation and interaction of physical objects or Tangible User Interfaces.*

There are several lessons from TUI research that can be applied to AR interaction design. Kato et al. (2000) list the following guidelines:

- Object affordances should match the physical constraints of the object to the requirements of the task.
- The ability to support parallel activity where multiple objects or interface elements are being manipulated at once.
- Support for physically based interaction techniques (such as using object proximity or spatial relations).
- The form of objects should encourage and support spatial manipulation.
- Support for multi-handed interaction.

2.3.5 AR Software Development Kits (SDKs)

A number of software development kits are available for assisting in the development of augmented reality applications. Of particular note are ARToolKit and Vuforia.

ARToolKit is a popular AR library offering both fiducial marker and NFT functionality. It was originally developed by Dr. Hirokazu Kato and currently exists in commercial and open source versions. The freely available open-sourced ARToolKit Version 2.x only provides fiducial marker tracking, however (ARToolworks 2012). ARToolKit 2.x has not been updated since 2007 and has certain limitations including range and pattern complexity trade-offs, minimal tolerance for partial marker occlusion and variations in lighting (HITLab 2006; ARTag 2006). It is also prone to misidentifying markers, jumping marker identity from one to another, or simply falsely detecting any black quadrilateral regions in a scene as markers (Fiala 2004).

Vuforia is an AR toolkit for mobile devices first released in 2010 by Qualcomm. Vuforia utilises NFT techniques to track pre-analysed ImageTargets (seen in Figure 2.8) as well as supporting frame markers, a type of fiducial marker that is defined by a bounding square only, allowing arbitrary non-

tracked elements to appear within the marker (see Figure 2.7). ImageTargets are more robust to partial occlusion, but due to processing demands only five can be tracked simultaneously at the time of writing (Qualcomm 2013). Frame markers, while not as robust to occlusion, track better at smaller sizes than ImageTargets, and there is no limit imposed on simultaneous frame marker tracking.

Vuforia exists both as a Software Development Kit (SDK) in its own right and also as an extension for Unity3D (also known simply as "Unity"), a popular 3D game engine (Unity Technologies 2012; Qualcomm 2012).

2.4 AR in Healthcare Simulation

AR has been used for many training applications in healthcare. Some relevant examples are discussed in this section.

One technique that is very useful in the field of medicine and healthcare simulation is using AR to visualise a simulation of organs and processes inside the body. Sielhorst, Obst & Burgkart (2004) developed a mixed reality childbirth delivery simulator, pictured in Figure 2.18. The system combines a physical delivery simulator that includes a physical model of the baby's head with an AR view of a virtual baby still inside the birth channel.

Hamza-Lup, Rolland & Hughes (2004) also use this internal view technique, in this case to assist with training in emergency airway management (intubation). Figure 2.19 shows the virtual lungs and trachea superimposed onto the mannequin. The author states that AR "allows students to actually 'see' the internal anatomy and therefore better understand their actions on a human patient simulator (HPS)."

Blum et al. (2009) developed an AR prototype to provide a "contextual in-situ visualisation" of Ultrasound slices using a mannequin, shown in Figure 2.21. They propose techniques for utilising such a simulator for training.

None of these prototypes listed so far have as yet undergone any form of validation in terms of training ability. This was often found to be the case with AR healthcare training simulator work, possibly due to the relatively new field that it is.

Figure 2.18: A Mixed Reality Delivery Simulator, showing the view through the HMD on the screen (Sielhorst, Obst & Burgkart 2004)

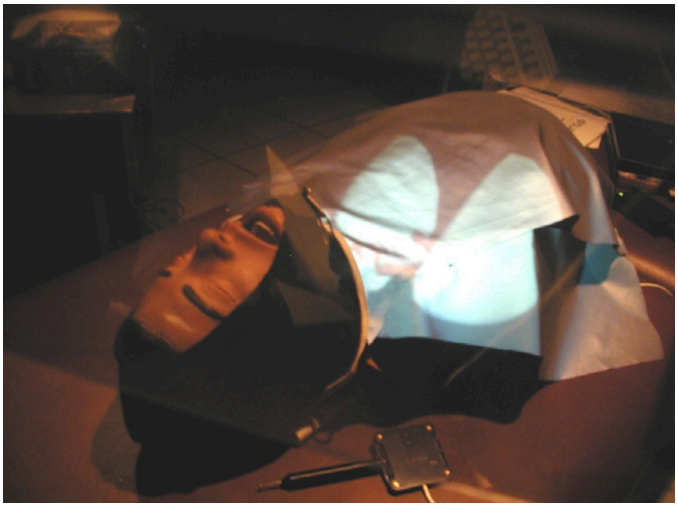


Figure 2.19: An Augmented Reality Airway Management simulation (Hamza-Lup, Rolland & Hughes 2004)

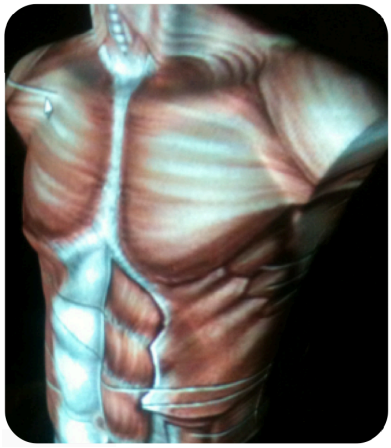


Figure 2.20: A Spatial Augmented Reality Mannequin (UniSA ITEK 2013)

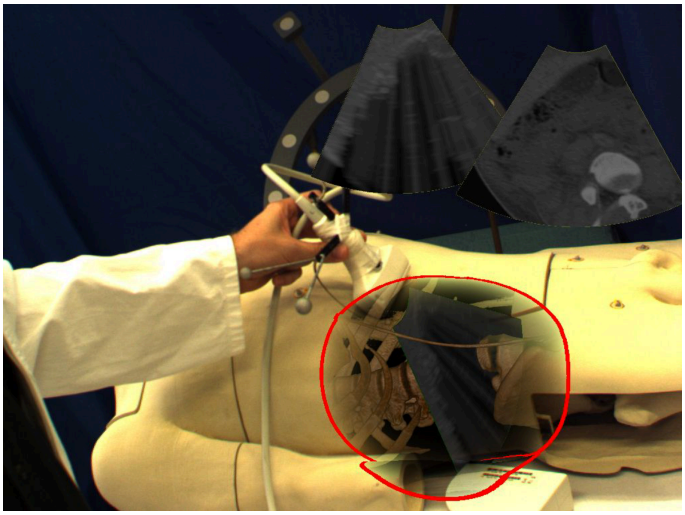


Figure 2.21: Augmented Reality Ultrasound Simulator (Blum et al. 2009)

Another feature these examples have in common, is that they utilise an AR layer on top of a physical simulator, employing a tangible physical interface. The breast exam simulator discussed earlier (Figure 2.2) is another example of this. In this case the AR layer is designed to facilitate a simulation of interaction with the patient to augment the simulation of the technical skill (the breast exam).

Figure 2.20 depicts a Spatial AR mannequin created by the University of South Australia's ITEK (2013), utilising multiple projectors to augment a very basic matte mannequin model that really serves simply as a 3-dimensional screen for augmentations. This can be used to easily represent patients from diverse demographics across age, gender, race, size and body weight, as well as being able to augment the 3D shape with educational diagrams of internal organs as shown in the figure.

Botden et al. (2007) took an interesting approach to laparoscopic simulation. Traditionally "box trainers" have been used, containing a physical arrangement of objects tha require some task to be performed through the use of laparoscopic tools. More recently virtual reality simulators have gained traction due to the increased realism afforded. Although these typically employ a haptic interface with force feedback, the physical realism is still limited. Botden et al. evaluated an AR laparoscopic simulator, employing a physical box trainer augmented with virtual graphics. This affords a realistic tangible interface for performing high dexterity tasks while also providing a realistic visual simulation through AR at the same time. A comparison study involving user testing with novices and experts concluded that the AR laparoscopic simulator was superior to the VR simulator.

Nilsson & Johansson (2007) conducted a study into the user acceptance of AR training tools in hospitals. Video see-through HMDs were used to provide training in the setting up of a piece of specialised equipment. The study used a questionnaire with multiple Likert items combined together to provided graded answers to the two primary questions: Did participants want to use AR training of this kind in their work, and did they find the training fun. The sample size was small, but results indicated that users felt positively towards both questions.

The use of AR for healthcare simulation is a growing field, with plenty of new ground being made. More work is required both in terms of simulator sophistication, as well as validation assessment.

2.5 Research Methods

Three main classes of research method exist: quantitative methods, qualitative methods, and, more recently, mixed methods.

Quantitative methods typically utilise a large sample of well-structured data and apply statistical methods to provide evidence to support or refute an existing theory. However, quantitative studies are a poor choice where there is a need to explore the reasons behind a phenomenon or where the development of new theory is needed (Creswell & Plano Clark 2007).

Qualitative methods, on the other hand, are suited to exploring relatively unstructured data by discovering themes and patterns inductively, and can therefore be used to develop new theories for explaining observed phenomena. Qualitative methods have limited ability, however, to evaluate the generalisability of findings over a population beyond the context of those individuals, sites or places directly involved in a study (Creswell 2009).

2.5.1 Qualitative Methods

Qualitative research asks open-ended, relatively unstructured questions and uses exploratory analysis techniques to discover patterns and develop new theories.

Interviews

Interviews are a useful data collection technique that allows a researcher to obtain in-depth, detailed information from participants about a topic. Interviews are usually conducted one-on-one. The level of structure used varies considerably, and is chosen according to the goals of the research (Cairns & Cox 2008).

Structured interviews employ a pre-prepared list of questions and do not deviate from a set format. Keeping the format consistent minimises bias and allows comparisons to be made between participants, but is less likely to reveal new concepts that were unknown prior to the interview. Structured interviews are sometimes called *researcher-administered surveys,* as they are essentially a questionnaire in the form of an interview. The advantage of this over a self-administered survey is that participants can seek clarification, reducing the risk of misunderstanding questions (Patton 2001).

Semi-structured interviews allow some flexibility to explore issues that emerge during the interview. A list of questions is still used but the researcher is not constrained to a set format. This allows all predetermined topics to be covered while also allowing room for exploration of new ideas.

Unstructured interviews have only a very broad sense of the topic prior to the interview. There may be only a single question presented at the beginning of the interview. From there the researcher is free to guide the conversation along any paths of interest (Cairns & Cox 2008).

In qualitative inquiry the researcher is the instrument (Patton 2001), so it is crucial that potential sources of bias be minimised. Interviewers must be diligent in avoiding asking leading questions, as well as questions that invite a socially desirable response (Cairns & Cox 2008).

Qualitative Analysis

The aim of qualitative data analysis is to gain a deep understanding of the data collected. Many researchers adopt a generic qualitative analysis process that centres around identifying themes and description from the data. This generic process is often adapted to suit the particular needs of the research. Creswell (2009) suggests the following steps be considered in qualitative analysis:

Step 1. *Organise and prepare* the data for analysis. This may involve, for example, transcribing interviews and typing up notes.
Step 2. Read through all the data to obtain a *general sense* of the information.
Step 3. Employ a *coding process* to organise and categorise the material.
Step 4. Develop *themes and descriptions* from the coded data.
Step 5. Develop *representations* of the themes and descriptions. This may be in the form of a narrative or discussion and may include visuals such as figures or tables.
Step 6. *Interpret* the meaning of the data, asking, “What were the lessons learned?” and “What new questions need to be asked?” This might be presented as Conclusions and Further Work.

This pattern should be considered an iterative process; a researcher will revisit earlier steps multiple times to refine the analysis, building a deeper and deeper understanding of the data.

2.5.2 Quantitative Methods

Quantitative research asks well-defined, closed-ended questions and uses statistical analysis to build evidence that supports or refutes a hypothesis. The aim in quantitative research is to collect data in a consistent, standard manner to minimise any sources of bias (Patton 2001).

A common technique in human-computer interaction research is the use of questionnaires to gather standardised data from a group of participants.

Likert Scales

A Likert item is an ordinal response format often used in questionnaires to measure participants' attitudes or opinions toward a specific statement. Implementations vary, however the standard format involves five response anchors indicating the level of agreement with the statement (i.e. Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree) (Cairns & Cox 2008).

Ideally, multiple Likert items asking similar questions around the same topic are summed together in analysis to provide a better approximation of participants' opinions. This grouping of Likert items is called a Likert scale (Cairns & Cox 2008). For example, a set of five five-point Likert items are summed together to produce a Likert scale out of 25. A Likert scale carries more weight in terms of reliability and validity than individual Likert items. In fact, some argue that it is entirely inappropriate to consider the results of individual Likert items at all (Lowell (2007) compares the practise to an I.Q. test with a single question). Additionally, while a five-point Likert item should be considered ordinal data (where response anchors are ordered, but distance between anchors is uneven), a 25-point scale can be considered interval data (where distance between points is equal), enabling more meaningful statistical methods to be applied. Likert scales should be developed according to the research questions, with a separate scale for each core construct being examined. This produces a set of Likert items for each scale (Carifio & Perla 2007).

Statistical Methods

Likert scale data, being interval data, can be summarised by calculating the mean and standard deviation. Because Likert item data is merely ordinal, calculating the mean is inappropriate; the median or the mode are better measures of central tendency (Cairns & Cox 2008).

Presenting the mean only makes sense if data fits the normal distribution curve. Moreover, if the data for a given question is bimodal (for example, half of participants strongly agreed and the other half strongly disagreed) then no measure of central tendency gives a complete picture as to the nature of the results.

Frequency plots (for individual Likert items) or histograms (for a Likert scale) are graphs that provide an effective visualisation of the spread of responses for a given question regardless of distribution. Visual inspection of these graphs can also reveal whether data conforms to the normal distribution or not, facilitating the choice of further statistical tests. This can also be formally tested using goodness-of-fit tests such as Pearson's product-moment correlation co-efficient (Cairns & Cox 2008).

While individual Likert item data cannot provide conclusive evidence in isolation, results can be triangulated with other data to help build a case. Responses are often reported in terms of percentages across participants, e.g. "85 percent of users didn't find the help page advice useful" (Cairns & Cox 2008).

To test whether results from two different groups are significantly different or not there are two relevant tests: Student's t-test is used when data is parametric (fits the normal distribution), and the Mann-Whitney ranked sum test is used when data is non-parametric.

Scatterplots are a type of chart that can be used to help identify potential relationships between two variables. Provided data is parametric, the Pearson product-moment correlation coefficient measures the degree and direction of correlation, and can reveal whether the correlation is statistically significant (Cairns & Cox 2008).

2.5.3 Mixed Methods Research

Mixed methods, as its name suggests, combines quantitative (quan) and qualitative (qual) elements within a single piece of research. A mixed methods approach is desirable as it enables the differing strengths of quantitative and qualitative methods to be combined to overcome each other's weaknesses. Creswell & Plano Clark (2007) provide the following definition:

> Mixed methods research *is a research design with philosophical assumptions as well as methods of inquiry. As a methodology, it involves philosophical assumptions that guide the direction of the collection and analysis of data and the mixture of qualitative and quantitative approaches in many phases in the research process. As a method, it focuses on collecting, analyzing, and mixing both quantitative and qualitative*

> *data in a single study or series of studies. Its central premise is that the use of quantitative and qualitative approaches in combination provides a better understanding of research problems than either approach alone.*

There are many different ways of combining quantitative and qualitative methods when conducting mixed methods research. Creswell & Plano Clark (2007) divide these into four major types: Triangulation Design, Embedded Design, Explanatory Design, and Exploratory Design. In turn, each type has several variants. There are several key differentiating features: whether the quantitative and qualitative elements occur concurrently or sequentially, whether they have equal or unequal weighting, and whether mixing occurs early or late in the research process.

Each type of design has been developed according to the needs of the specific research questions in their respective studies. Triangulation design employs the two methods concurrently to corroborate or confirm findings. Embedded design uses a secondary form of data in a supportive role to the other, primary form of data. Explanatory design uses qualitative data to help explain or build upon quantitative results. Exploratory design uses qualitative data to guide the design of the quantitative phase.

There are two designs of relevance to this research: "Triangulation Design: Convergence Model" and "Exploratory Design: Instrument Development Model".

Triangulation Design: Convergence Model

Triangulation design is the most common and well-known approach in mixed methods design, and the convergence model is the most traditional of the four triangulation models (Creswell & Plano Clark 2007). The convergence model of triangulation design involves implementing the quantitative and qualitative methods during the same timeframe (concurrently), considering them with (typically) equal weight, and merging the data during the interpretation.

Each type of data is collected and analysed separately before being converged during interpretation, as shown in Figure 2.22. This contrasts with an alternative approach, employed by the Data Transformation Model, that mixes data by transforming one data type into the other before merging the data sets during the analysis (Creswell & Plano Clark 2007).

The purpose of this model is to provide well-substantiated conclusions about a single phenomenon. It is able to compare, validate, confirm, or corroborate quantitative results with qualitative findings.

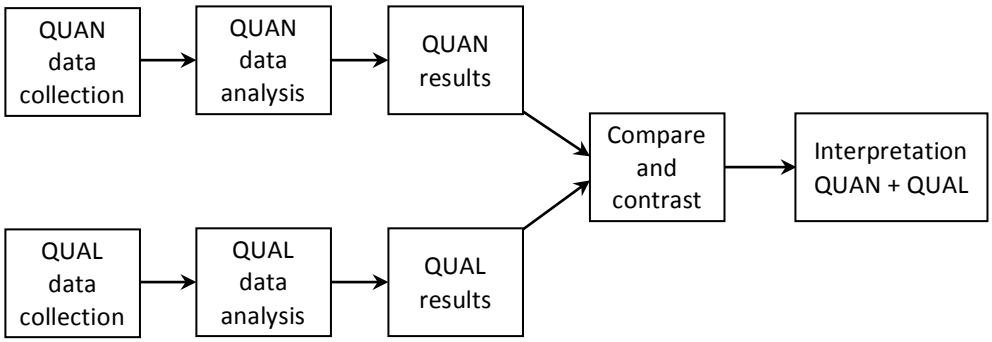


Figure 2.22: Triangulation Design: Convergence Model (Creswell & Plano Clark 2007)

One example of this research design from the literature can be found in a study by Nilsson & Johansson (2007), in which a questionnaire employing Likert-style and open-ended questions provided quantitative and qualitative data.

Another is Aggarwal et al.'s (2007) study examining a virtual reality laparoscopic simulator. Statistical analysis of quantitative data collected regarding participant performance in the simulator was analysed together with findings from a qualitative analysis of the video footage of the same.

Exploratory Design: Instrument Development Model

Exploratory Designs consist of two phases. The qualitative phase occurs first, the results of which inform the design of the second phase, which explores the phenomenon more deeply. The instrument development model, illustrated in Figure 2.23, is one of two common variants of exploratory design. In the initial qualitative phase, the research topic is explored with a few participants. The qualitative findings then guide the development of a quantitative survey instrument. This design typically places emphasis on the second phase (Creswell & Plano Clark 2007).

2.5.4 Approaches to Participant Recruitment

Quantitative research aims to obtain a representative sample of a population in order to generalise results to that population. To achieve this, recruitment methods aim to select participants randomly from the chosen population.

In qualitative research, however, it is common for participants to be purposefully selected in order to best help the researcher understand the problem under investigation (Creswell 2009).

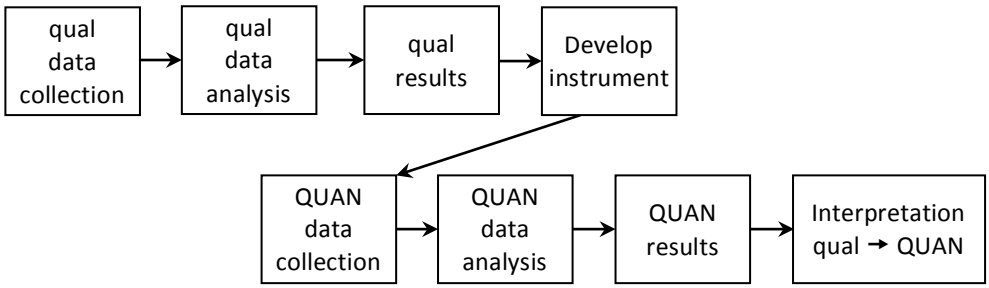


Figure 2.23: Exploratory Design: Instrument Development Model (QUAN emphasis) (Creswell & Plano Clark 2007)

Mixed methods research employs a selection method according to the dominant research paradigm in use and the suitability to the research problem.

2.6 Summary

This chapter has covered key topics in the literature that relate to the research problem.

We have learnt that Hospital Acquired Infections (HAIs) are a serious global problem and are a leading cause of death. Correct aseptic technique has been identified as a key factor in reducing HAIs in our healthcare facilities, yet the lack of immediate feedback when aseptic breaches occur means that healthcare workers are unable to learn from their mistakes, resulting in the perpetuation of bad habits.

Simulation as an educational training method has been shown to be of benefit in keeping healthcare workers' skills sharp, with feedback being a critical element for successful learning. Simulator validity has also been covered, as it is imperative that experience gained in simulation can be transferred accurately to the real thing.

Augmented Reality (AR) technology has been discussed, including the strengths and weaknesses of fiducial marker-based tracking and natural feature tracking approaches. A range of AR display techniques have been considered, with different configurations being appropriate for different applications. AR technology has been applied to a range of healthcare simulation applications, usually by augmenting existing simulation equipment (which provides a tangible interface) with additional graphical elements (eg. to improve realism and/or sense of presence).

Finally, the relative strengths of qualitative and quantitative research methods were discussed, along with strategies for combining both approaches in mixed methods research designs.

The review of the literature has also revealed that while simulation techniques have been used to assist with aseptic technique training in the form of gels/dyes and pompoms representing microbes, these approaches have inherent limitations. AR technology appears to be an ideal candidate for simulating a sterile environment. This is an approach that has not been previously explored, making this work novel.

3 Preliminary Study

The overall research design was comprised of two major phases, based on the instrument development model of exploratory mixed-methods design discussed in Section 2.5.1. A preliminary qualitative study, which is the focus of this chapter, was first used to gain an understanding of the problem domain, identify the requirements of the prototype system, and develop the research instrument (questionnaire) used in the evaluation study.

3.1 Methodology

The aim of the preliminary exploratory study was to identify key issues surrounding the learning of aseptic technique. The purpose was to inform both the design of the prototype AR system as well as the experimental design of the evaluation study.

The preliminary study employed a qualitative approach and consisted of three components: a review of relevant literature, informal interviews with staff members, and an observational study of students practising aseptic technique in the classroom.

3.1.1 Literature Review

Initially, an examination of relevant Nursing literature was undertaken including publications relating to Aseptic Technique, Infection Control, and Training approaches including Simulation. The findings from the literature are presented in section 2.1 and formed a basis for the remainder of the study.

Searches were performed through Google Scholar and the University of Tasmania Library's SUMMON combined search facility.

3.1.2 Staff Interviews

Secondly, informal interviews were held with School of Nursing and Midwifery staff involved in the teaching of aseptic technique. These interviews were highly unstructured and were primarily concerned with identifying typical

mistakes students make when attempting aseptic technique procedures, as observed by teaching staff.

A total of eight staff members were engaged in fairly open-ended conversations about aseptic technique training. Staff members were invited to participate who were currently (or recently) involved in aseptic technique training, and who had at least several years teaching experience. All had at least several years relevant clinical experience also. None had any previous experience with augmented reality technology but all employed simulation-based training in their teaching as part of the curriculum.

The researcher guided the discussions to focus on the following key topics:

1. What are the key aspects of aseptic technique that need be to correct?
2. What aspects of aseptic technique do students have the most trouble with?
3. What specific mistakes students commonly make?
4. What do students find difficult to understand or remember?
5. How is aseptic technique currently taught?
6. What difficulties are associated with teaching aseptic technique?

Various simulator design alternatives were also discussed, such as:

1. Whether it would be important to use real saline or not,
2. Whether swabs that were made rigid (so that markers could be attached) that can't be scrunched or folded would likely be a problem,
3. Whether the lack of hand or glove tracking would be an issue, and
4. Which AR display method would be most appropriate: HMD, projector-based, or Virtual Mirror configuration.

Some interviews were conducted individually, and some had staff members in groups of two or three. Handwritten notes were made by the researcher during each interview.

3.1.3 Observational Study of Students

Finally, an observational study was conducted of first year nursing students in Wound Management tutorials receiving instruction on and subsequently practising aseptic technique for the first time.

Tutorials began with the staff member teaching and demonstrating changing a wound dressing on a mannequin, focusing on correct aseptic technique. This was observed and videoed for reference.

Following the teacher demonstration students divided into groups of two-to-five and each had a turn at undertaking a wound dressing change with a mannequin. Observations were made of various students completing the task. Half the students were videoed with the camera on a tripod in front of them. For the other half the video camera was held by the researcher looking over-the-shoulder of the student to approximate their point-of-view, and the view that a HMD AR system would have if that display method was chosen.

Due to the researcher having a two-year break in the middle of the research, some interviews and tutorial observations were conducted in August 2009, and others were conducted in February 2012. This had the beneficial side effect of increasing the diversity and therefore generalisability of data gathered. In total eight staff were interviewed and nine students had a complete wound dressing change procedure videoed, though an estimated thirty or more students were observed to some degree from five different tutorials in two separate cohorts, under the instruction of three different staff members.

Eight of the students videoed were female, one was male. Ages were not recorded but most were in their early twenties, with a few in their thirties or forties. Anecdotally the sample seems representative of the cohort of students enrolled at the time.

3.2 Findings of the Preliminary Study

The findings of the three components of the preliminary study complemented one another.

Literature Review

Firstly, the literature showed that HAIs are a major concern and that one of the primary causes is poor aseptic technique by healthcare workers. It also showed that aseptic technique is difficult to learn using traditional methods, and that practise with feedback is the key to successful learning (Lewis 2009). Even experienced healthcare workers may not employ correct aseptic technique due to a lack of feedback (Friedman, Siddiqui & Katznelson 2008).

Staff Interviews

Secondly, informal interviews with staff from the School of Nursing and Midwifery (SNM), UTAS confirmed that aseptic technique was a common problem area for students, and identified several specific errors students often make. These can be broadly classified as either conceptual misunderstandings or subconscious errors, and are discussed in more detail below.

The interviews also discussed prototype design issues. The consensus was that the pouring of real saline, while important to practise, was not a critical part of the procedure in light of the problems that would be caused by wet markers. Similarly, although folding/scrunching swabs is necessary, the need to facilitate tracking was understood and pre-folded markers were deemed an adequate solution.

Hand tracking was regarded as an important requirement as the hands are the highest source of subconscious error. It was felt, however, that there would still be value in a system that excluded this, particularly if users were asked to complete the procedure using non-touch. Non-touch technique requires that forceps be used for all manipulation of sterile objects rather than touching them directly. Sterile gloves are not required, saving on manufacturing cost and waste (sterile gloves are single-use). Non-sterile gloves are generally still used, but primarily as a safety precaution for the healthcare worker rather than it being of benefit to the patient.

There was a strong preference against HMDs as a display method due to the bulkiness of current devices and the mediated view of real objects. A simple test was conducted where a user wore a video-see-through HMD with a simple direct video feed (no augmentations) and tried to interact with forceps, swabs etc. It proved very difficult for users to reliably align objects in 3-dimensional space accurately.

Observational Study of Students

Thirdly, students from SNM were observed in introductory wound management tutorials. Instructors demonstrated how to change a wound dressing on a mannequin while employing correct aseptic technique, then students each practised the procedure in small groups of two-to-five. Students took an average of five minutes to complete the wound dressing procedure

Being in small groups, students were able to receive feedback from their classmates as they practised. However, peers are not experts. While the teacher spent a short time with each group, there was only minimal opportunity for errors to be detected by them, which otherwise often went unchallenged. Even if the student's peers did notice an error, they were sometimes reluctant to say anything due to uncertainty regarding whether an error did in fact occur, or whether the perceived severity of the error warranted mentioning.

The findings from each of these three elements were analysed together to construct a thorough understanding of the key issues surrounding the learning of aseptic technique. These findings guided the design of the prototype system, as well as the design of the evaluation study. Common errors can be broadly

categorised into two types: conceptual misunderstandings, and subconscious errors.

3.2.1 Conceptual Misunderstandings

Staff noted that students often have trouble *identifying the boundaries of the sterile field*, revealing confusion about what it includes and what it does not. Knowing and keeping track of what is sterile and what is not sterile is key to preventing contamination.

The sterile field incorporates everything that is sterile. In the context of a wound dressing procedure, this refers to the blue sterile field sheet and everything on it. A several-centimetre-wide zone protruding in from the edges of the sheet should be considered non-sterile, however, due to potential contamination from the surface the sheet is placed on.

Adding to student confusion is the existence of *multiple competing theories underpinning aseptic practice*. Staff confirmed, as discussed in section 2.1.2, that the transfer technique (ie. "clean/dirty method") is still required in many healthcare institutions despite evidence that it does not improve patient safety (Gillespie & Fenwick 2009). As a result, students are required to learn this approach in addition to wound field concept, unnecessarily complicating the issue.

Students have been known to consider the trolley surface to be part of the sterile field, possibly because one of the first steps is to wipe it down with an alcohol-wipe. This only makes it clean, however, not sterile. Figure 3.1a shows a dressing and a pair of forceps that have been placed too close to the edge of the sterile field. While the dressing being dropped into this position occurred accidentally, the student failed to comment on the fact that it had become contaminated, and applied the contaminated dressing anyway. Nor did any of her peers draw attention to this error.

The sterile field actually extends to the ceiling above any sterile surface, due to the potential for microorganisms to fall from non-sterile objects. This is known as "*fallout*". While risk of fallout is difficult to avoid completely—in some cases it is necessary to position non-sterile objects above the sterile field, such as when pouring saline—it should be avoided as much as possible. Figure 3.1b shows a student reaching over a sterile field to put gloves on.

Figure 3.1c depicts a saline sachet having been accidentally dropped into the tray the saline was being poured into. While this was accidental, the saline sachet was also being held too close to the tray to begin with, increasing the risk

of fallout. In interviews, staff noted that the saline sachet should be held no closer than 5cm above the tray.

Figure 3.1d shows a dressing being slid out from its packet. This is a problem as the edges of the pack are not sterile. The correct technique is to open the pack from the bottom, dropping the contents cleanly onto the sterile field without it touching the edges of the packaging.

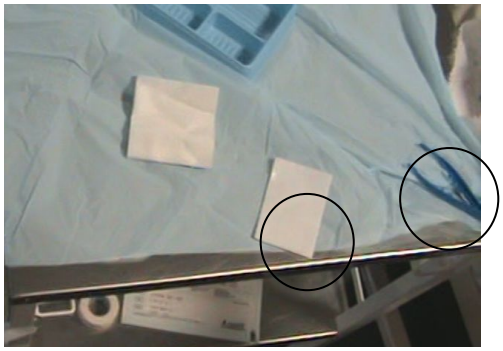
Forceps and sterile gloves can also be contaminated by touching the rubbish bag when discarding an item, such as a used swab. Students must drop items into the rubbish bag from several centimetres above it to avoid contamination. In some cases this may be due to subconscious error but is included here as it is often overlooked.

Another common error identified by staff stemming from conceptual misunderstanding is the *placement of unopened packs on the sterile field sheet*. While the contents of the packs are sterile (eg. saline or a wound dressing), the packaging they come in is not. Because of this, all necessary packs should be opened and their contents placed safely in the sterile field prior to direct interaction with the sterile items themselves.

Some staff also commented that in general students played down the significance of making an error, not understanding the 'snowball' effect that making an error has. For example, if a swab accidentally becomes contaminated by being dropped too close to the boundary of the sterile field, but is then brought back into the sterile area with sterile forceps, the forceps will become contaminated and the sterile field will become contaminated. If unchecked this one small initial error will ultimately result in the wound becoming contaminated, leading to possible infection.

3.2.2 Subconscious Errors

Teaching staff also identified *subconscious touches* as a frequent source of error for students. The most common example was students touching themselves while wearing sterile gloves. For example, students might rub their nose, adjust their glasses, or touch their hair, in each case being unaware that they have done so. Even when challenged by classmates or instructors, students often do not recall having subconsciously touched something they should not have.

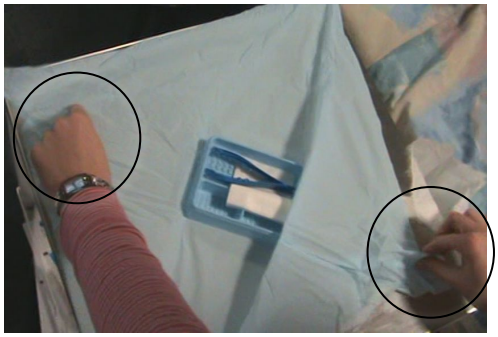


(a) Dressing and forceps placed too close to edge of sterile field

(b) Arm reaching across sterile field risking fallout unnecessarily

(c) Saline sachet accidentally dropped into tray

(d) Dressing slid across non-sterile edge of packet



(e) Bare fingers used to adjust sterile field sheet

(f) Sterile glove touching non-sterile packaging

(g) Sterile glove touching bare skin

Figure 3.1: Stills from footage of students practising wound care showing common aseptic technique errors.

Conceptual Errors	ARSterileSim
Drop or touch packaging onto sterile field	Yes
Open sterile items (swabs, dressing) onto table/too close to edge	Yes
Touching rubbish bag with forceps	Yes
Crossing the area above sterile field unnecessarily (“*fallout*”)	Partial

Subconscious Errors	ARSterileSim
Touch sterile object with bare hands/non-sterile gloves	No
Touch self with sterile gloves on (e.g. scratch nose, adjust glasses)	No
Touch non-sterile surface with sterile gloves on	No
Touch non-sterile surface with sterile forceps	Yes

Table 3.1: Typical errors made by students, and whether ARSterileSim is designed to detect each type of error.

This behaviour was observed in the classroom: Figure 3.1e shows a student using bare fingers to adjust the position of the sterile field sheet. Figure 3.1f shows a student using a sterile-gloved hand to adjust the position of a pack that has become contaminated due to contact with the bed sheets. In Figure 3.1g, a student has contaminated the sterile glove on their right hand by touching the bare skin of their left hand while trying to put on the glove for that hand. In each case the student did not realise they had made an error.

In everyday contexts these subconscious touches are perfectly acceptable. Thus, students have never been required to be conscious of them before. Retraining the brain to be aware of movements at this level of detail requires mindful practise with appropriate feedback.

3.3 Summary

The preliminary study consisted of informal interviews with staff and observations of students in an effort to discover the key issues related to introductory aseptic technique training and problem points for students. A summary of the typical errors students make can be seen in Table 3.1. The study revealed common conceptual misunderstandings held by students, all stemming from an inaccurate or incomplete understanding of the boundaries of the sterile field. It also identified common subconscious errors, including touching their own body while wearing sterile gloves and touching sterile objects while not wearing sterile gloves.

Overall students each made several errors on average. Some were more common, such as placing objects too close to the edge of the sterile field and cross-

ing the area above the sterile field unnecessarily. Others were only observed once or twice, such as touching the sterile field with an emptied packet. The sample size was quite small, but the findings are validated by the interviews with staff who predicted all the errors that were found.

4 ARSterileSim Prototype System

The preliminary study identified key areas where students encounter difficulties maintaining aseptic technique during wound care. The findings were used to justify and guide the development of a prototype AR sterile environment simulator ("ARSterileSim") that aims to assist students with these issues. This chapter describes the developed system and the rationale for the design decisions that were made.

4.1 Overview

The ARSterileSim prototype system simulates a sterile environment, tracking sterile and non-sterile objects in real 3D space. The system utilises visual markers attached to objects used in a basic wound dressing procedure, as taught to first year nursing students in the School of Nursing and Midwifery, UTAS. Each object is coded to be initially either sterile or contaminated, and the system keeps track of each object's status throughout the simulation. Sterile objects are represented by subtle pale blue shading (25% opacity); contaminated objects are highlighted in red (35% opacity).

A screenshot of the development environment can be seen in Figure 4.1. In this image the physical objects that are tracked are indicated together with the virtual geometry used to represent each object. Blue and red indicate the initial contaminated status of each object.

The system employs Tangible User Interface idioms, allowing parallel activity of multiple objects, and triggering interaction from physical spatial relations: When a contaminated object touches (collides with) a sterile object, the sterile object becomes contaminated, triggering a red flash and an audio alert. Contamination can then spread from the newly contaminated objects to other sterile objects they come in contact with. Screenshots from the prototype showing this process can be seen in Figure 4.2.

The simulation is powered by a relatively simple script that is attached to each tracked object. Unity's built-in collision detection system is utilised as part of this. The effective algorithm used is as follows:

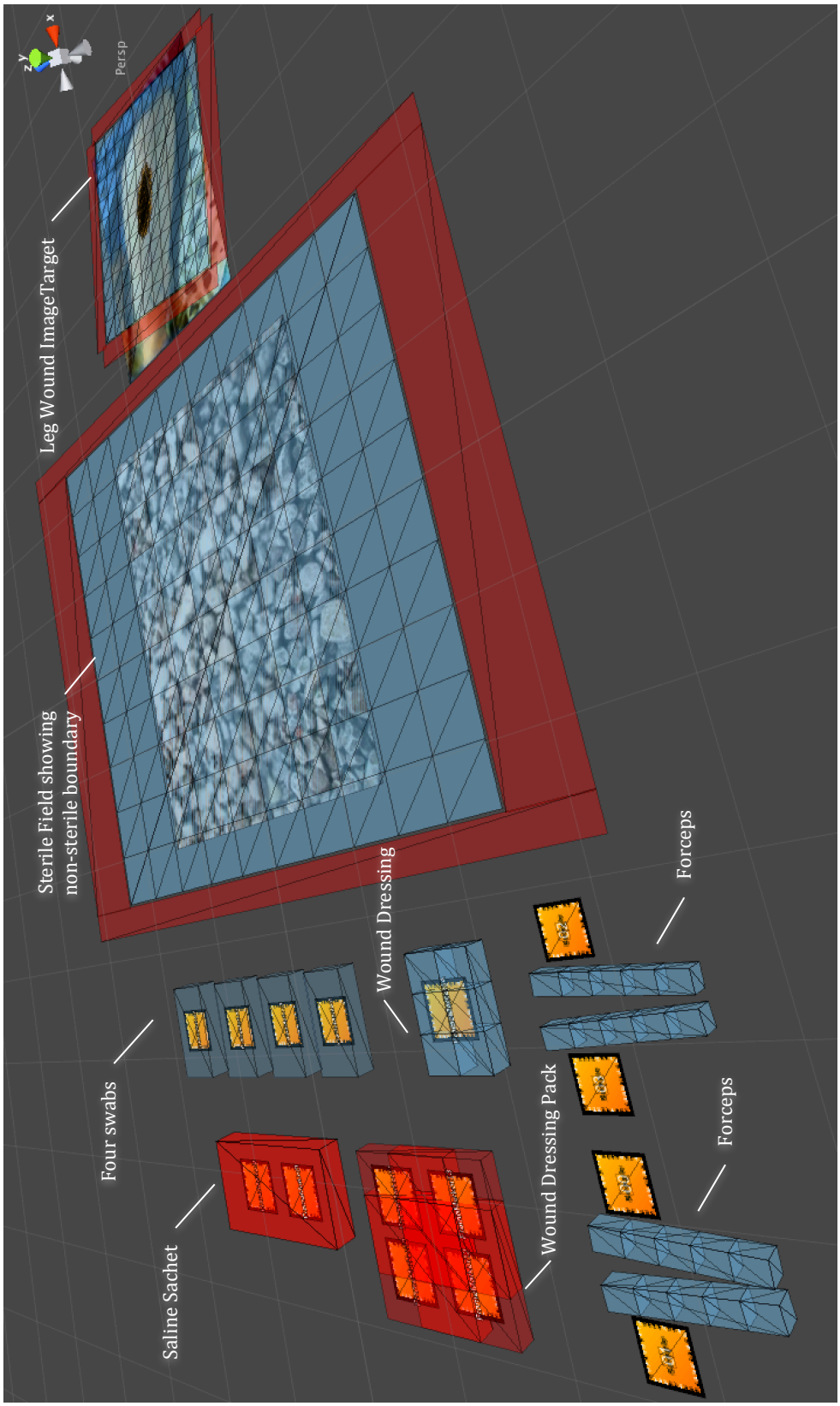


Figure 4.1: ARSterileSim virtual object design in the Unity development environment

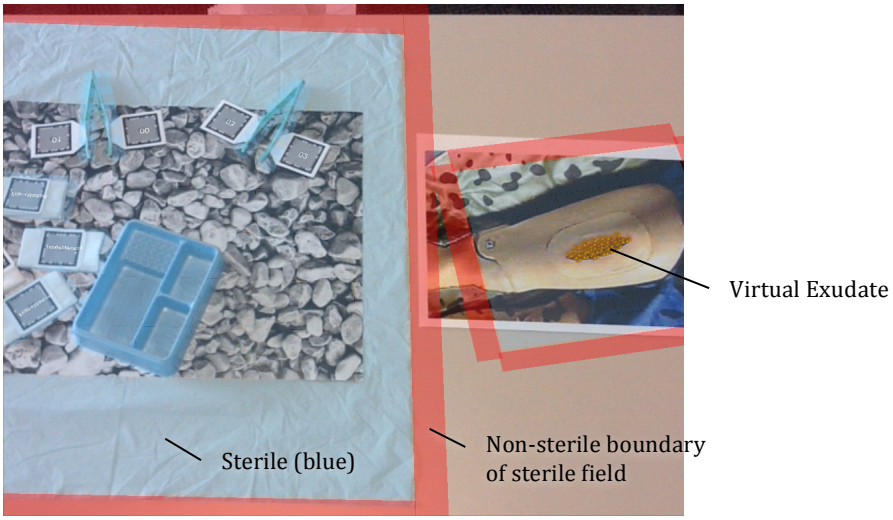
```
Whenever this object (that the script is attached to)
collides with some other object:
{
       If this object is sterile and the other object is
       contaminated:
       {
              Set this object to 'contaminated'.
              Trigger an animation to fade the alpha channel
              from full opacity to 35% opacity over 4
              seconds.
              Play the alert audio clip.
       }
}
```

The actual code for this script can be found in SterileObject.cs in Appendix D.

This script simulates a sterile environment in a similar fashion to the way a physics simulation simulates weight, momentum and gravity, in the sense that a universal set of rules is applied to every object indiscriminately. The simulator does not need to know whether the sterile region it is considering is representing a swab or a wound dressing pack. All it needs to know is its location within a unified coordinate system, and whether it is sterile or not.

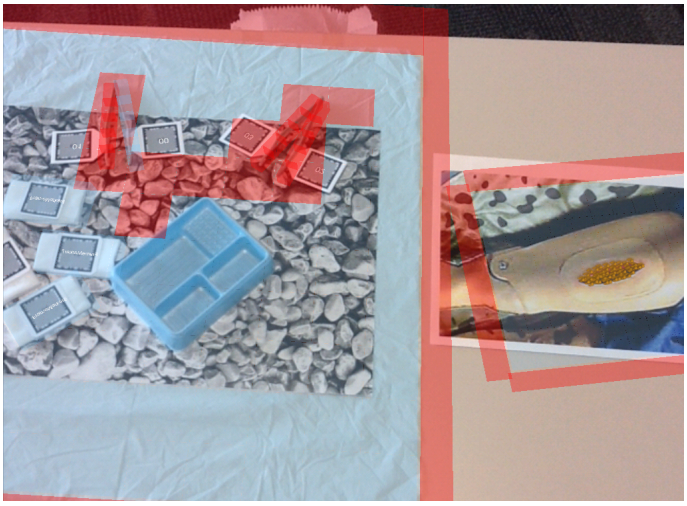
Some sterile objects are divided into a grid of sterile blocks (visible in Figure 4.1), allowing part of an object to become contaminated while the rest remains sterile. This is particularly important in relation to the sterile field sheet as it is possible to contaminate part of it but still complete the wound dressing change without contaminating the wound itself, which in the end is all that matters.

It should be noted that ARSterileSim is *not* designed to guide users through a step-by-step procedure. The system has no concept of the procedure of the task to be completed, or the steps required. It is solely focussed on simulating the sterile environment: tracking objects and detecting when they become contaminated. The only exception to this is the addition of virtual exudate to the simulated wound (visible in Figure 4.2). The virtual exudate disappears when 'wiped' (technically 'collided') with a swab (assuming the swab is being tracked accurately). While not strictly part of the teaching of aseptic technique, it was included as an example of the kind of added realism augmented reality could offer this domain.



(a) Initial setup.

(b) Forceps placed on non-sterile boundary have become contaminated.



(c) Non-sterile forceps spread contamination further.

Figure 4.2: ARSterileSim Prototype screenshots, showing how one error leads to the spread of contamination.

4.2 Design Considerations from the Preliminary Study

Table 3.1 summarises the key errors students make when learning aseptic technique, and indicates which of these ARSterileSim aims to incorporate into its design. As discussed in the previous chapter, these errors were divided into two categories: conceptual misunderstandings and subconscious errors.

4.2.1 Conceptual Misunderstandings

An awareness of which objects are sterile and which are non-sterile is key to correct conceptual misunderstanding and develop a correct mental model, so the prototype was designed to present this information clearly in real-time. Blue and red colour-coding has been successfully used in other work to represent sterile and non-sterile areas respectively so this visualisation was adopted (Kaska 2010). If students are uncertain about an object they merely need to look at it via the virtual mirror and observe its colour. The goal is that the knowledge students gain from using ARSterileSim be transferred from simulation to a clinical setting. Conceptually, students would imagine the colour coding and audio alerts, effectively running the simulation in their head, ideally giving them an instinctive awareness of the sterile environment.

Drop or touch packaging onto sterile field

As discussed above, one common error was the placing of non-sterile packaging on the sterile field sheet, or holding packs too close to the sheet while opening them. These were both addressed by placing markers on packs so that these errors could be detected.

Open sterile items (swabs, dressing) onto table/too close to edge

Another common error was placing sterile objects too close to the edge of the sterile field. To address this, a boundary of approximately 2cm around the sterile field sheet was coded as being non-sterile. Technically this non-sterile area extends over the entire surface that the sterile field is placed on, but it was important that it did not overlap with the wound model, so 2cm was deemed sufficient for the prototype. Figure 4.2b shows this non-sterile boundary along with a pair of forceps that have been placed on the boundary and have become contaminated as a result.

Touching rubbish bag with forceps

Figure 4.2b also illustrates the placement of the rubbish bag with respect to the non-sterile boundary of the sterile field. This ensures sterile items, includ-

ing forceps, will become contaminated should they move too close to the rubbish bag opening when discarding items.

Crossing the area above sterile field unnecessarily (*"fallout"*)

The sterile field sheet detection zone was defined with a small amount of extra height to ensure detection of non-sterile objects held too close. Although it is desirable to minimise entry of any non-sterile object above sterile surfaces to reduce the risk of fallout, it is sometimes necessary (for example, when pouring the saline) so this extra height was limited to approximately 2cm.

4.2.2 Subconscious Errors

Subconscious errors occur, by definition, without the student being aware of them. To address this, an audio alert was employed whenever an object becomes contaminated. The contaminated object also flashes bright red for a few seconds before fading to semi-transparent red, so that freshly contaminated objects can be distinguished from those which were already non-sterile. This is a technique for highlighting change borrowed from web interaction design.

Touch objects with hands or gloves

The preliminary study identified three important contamination vectors relating to subconscious touching of objects with either bare hands or sterile-or-non-sterile gloves. However, accurately tracking hands and body parts is essentially impossible to accomplish using traditional AR tracking markers. This was worked around by specifying that non-touch technique be used with the simulator, as suggested in staff interviews in section 3.2.

An active infrared depth sensor such as the Kinect is a good candidate for solving the problem of hand tracking, however this presents further challenges such as segmenting and uniquely identifying objects from depth maps over time so as to keep track of their sterility. Marker-based tracking would likely still be required for some items to identify them, and unifying the two approaches is non-trivial. In an effort to reduce complexity and focus on the research question of establishing a rationale for using AR for aseptic technique training, hands and body tracking was omitted from this first prototype and is left to further work (see section 6.4.2).

Touch non-sterile surface with sterile forceps

As mentioned above, forceps essentially act as the user's hands for all sterile object manipulations so it was important that these be tracked. Markers were attached to each arm of the forceps using stiff card, as pictured in Figure 4.2a.

The attachments were necessary due to a minimum marker size (discussed below) and were attached in a position designed to allow the user to hold the forceps as normally as possible, and also keep the tips free to grasp objects.

4.3 Marker Design

Vuforia provides two types of markers: ImageTargets and Frame Markers. ImageTargets were used to track the sterile field sheet and the virtual wound due to their ability to maintain tracking despite significant occlusion. All other tracked objects utilised frame markers, as these work better at smaller sizes and are less resource intensive.

4.3.1 ImageTargets

ImageTargets work well at large sizes and are robust to occlusion, but are processor intensive. For performance reasons Vuforia therefore limits simultaneous tracking of ImageTargets to five or less. The robustness to occlusion makes them ideal for tracking the blue sterile field sheet and the wound, which need to maintain tracking despite multiple objects causing occlusion at any given time.

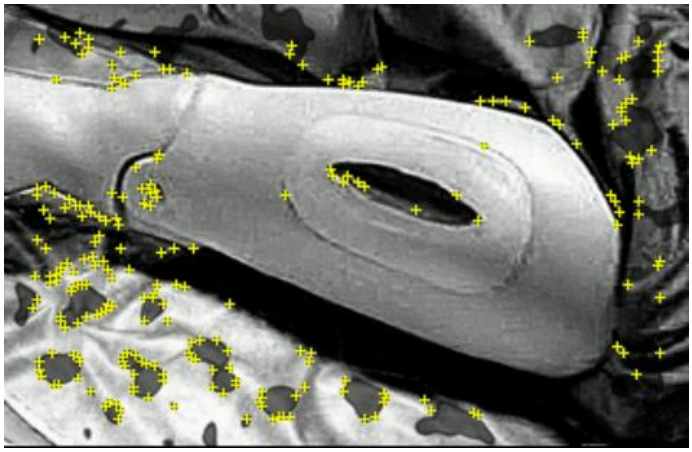
For the sterile field sheet the “Stones” ImageTarget included with the Vuforia SDK was used, printed on A3 paper. The feature analysis shown in Figure 2.8 in Chapter 2 shows that this design is feature-dense, making it a good candidate for this application. It is also relatively visually unobtrusive, particularly as it was printed in greyscale.

As this was the largest and most detailed tracking target, it was set as Vuforia’s unified coordinate system origin. This means that all other objects have their position in 3D space calculated relative to the Stones tracking marker. A unified coordinate system is essential for collision detection to work properly.

The wound was represented by an ImageTarget based on a photo that was taken of a mannequin’s leg with a wound module exposed. Using a photo rather than an actual mannequin provided a convenient tracking source as well as making the system more portable.

To improve tracking the original photo underwent sharpness filtering and contrast widening. Dark blobs were also drawn on directly. The final version along with a feature analysis is depicted in Figure 4.3. The Leg Wound ImageTarget was printed on A4 sized paper in full colour.

(a) As printed



(b) Vuforia feature analysis

Figure 4.3: Leg Wound Image Target

4.3.2 Frame Markers

Frame markers were used for all other trackable objects including swabs, the wound dressing and pack, the saline pack, and forceps. All frame markers were 4cm square except for those attached to the forceps and swabs, which due to physical size constraints were slightly smaller at 3.5cm square. These sizes were chosen because they were the largest practical size for attaching to the objects in question, and tests at smaller sizes resulted in much less robust tracking. Multiple frame markers were attached to objects where possible to improve robustness: This configuration allows only one marker in a set to be accurately tracked in order to track the whole object.

4.4 System Design

4.4.1 AR Display Configuration

A video see-through spatial AR display (i.e. a screen) utilising a virtual mirror metaphor configuration was chosen as it affords minimal disruption of the user's natural interaction with equipment whilst providing an easily comprehensible feedback metaphor.

HMDs were also considered but these, particularly the video-see-through variety, impede the user's view of the real world. Depth perception is particularly impeded, which is critical for the fine-grained manipulation of objects required for correct aseptic technique. Staff members specifically indicated a preference against HMDs (see section 3.2). A handheld device approach was also rejected for similar reasons.

A projector-based approach was considered, however this requires careful calibration and is less portable than the virtual mirror approach. Additionally, light projected onto markers can interfere with tracking quality, which is important to maximise. A projector-based approach would be worth further investigation but is left to further work.

4.4.2 Platform and SDK

The prototype was developed in Unity Technology's Unity game engine version 3.5 (Unity Technologies 2012) with Qualcomm's Vuforia Augmented Reality extension version 1.5.9 (Qualcomm 2012). As discussed in Section 2.3.5, Vuforia is a modern AR SDK that offers an affordable high quality alternative that is relatively easy to develop with. Unity is a 3D game engine that was chosen as provides an excellent environment for rapid prototyping of 3D interactive applications. Unity scripts for all interactive features were written in C#.

A limitation of Vuforia, at the time of development, was that it could only be deployed on iOS and Android powered devices. Qualcomm is primarily a mobile chipset manufacturing company, so their goal in developing Vuforia is to promote the mobile device market, hence their focus on mobile devices. Without this limitation a desktop computer would have been the obvious choice of platform due to superior processing power. An advantage of using a mobile device, however, is that the system is very portable.

The system was deployed on an Apple iPad 2 as this was the best supported device in terms of tracking quality and frame rate. While the third generation iPad was also available at the time of the evaluation study, the app frame rate performance was actually worse than the iPad 2. This is likely due to the

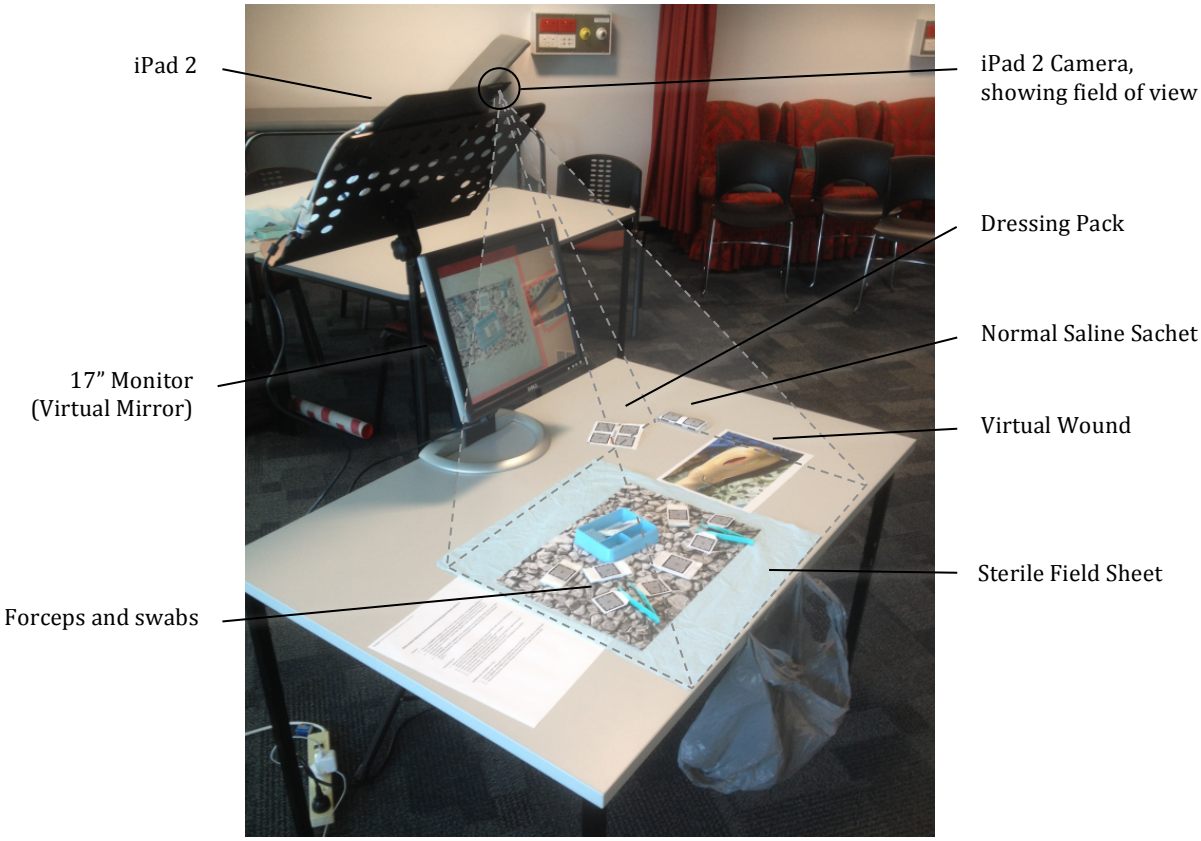


Figure 4.4: ARSterileSim Prototype Physical Setup

quadrupled resolution of the newer iPad (2048x1536 "retina display" compared with 1024x768 on the iPad 2), despite having a faster processor. The iPad was mounted on a stand with the integrated rear-facing camera approximately one metre diagonally away from the user's work area. An Apple 30-pin to VGA adapter was used to connect the iPad to a 17" 4:3 LCD computer monitor. The video feed was flipped horizontally via Unity script in order to simulate a mirror. The physical setup is pictured in Figure 4.4.

4.4.3 Known Technical Limitations

The ARSterileSim system is an experimental prototype only, created for the purpose of illustrating the underlying approach to teaching aseptic technique and subsequently exploring the validity of that approach. There are a number of known limitations that are discussed in this section.

Tracking reliability

At present Vuforia selects a video frame resolution for tracking automatically based on available camera resolution and processing power. On the iPad 2 this equates to 640x480 size frames (video is displayed at a resolution of

1024x768). This resolution cannot be changed by the programmer. While this results in a good frame-rate, it also requires markers to be larger and/or closer to the camera such that marker detail is sufficiently visible for reliable tracking. Various marker sizes were tested and a compromise between size and tracking performance was reached. Future hardware and software implementations will undoubtedly allow tracking from higher resolution camera frames, allowing better tracking of physically smaller markers.

Additionally, lighting conditions play a key role in tracking performance. To combat this, lighting conditions were tested and optimised prior to testing with participants.

Field-of-view limitations

As mentioned above, it was important to place the camera as close to markers as possible to maximise tracking accuracy. However, it was also desirable to maximise field-of-view to capture every action the user makes. Again, the camera distance from the work surface was chosen according to a compromise between tracking accuracy and field-of-view.

Untracked objects

ARSterileSim relies on visual markers to achieve tracking. This approach suits rigid objects, such as dressing packs and forceps, but does not lend itself well to complex or malleable objects, such as saline, swabs, and the user's hands and body.

For the purposes of the prototype, participants were asked to pretend to open the sachet of normal saline and then imagine the presence of saline in the tray. Swabs are typically folded or scrunched up when conducting wound care, making them difficult to track. Again, for the purposes of the prototype, swabs were pre-folded in half and a marker attached to either side.

System Delay and Latency

Inherent in any AR system is latency in the processing pipeline. Video capture, frame analysis, pose estimation, and rendering each take a certain amount of processing time, which can result in delay that is perceivable to the user. Effort was therefore made to keep the number of tracked items low and to minimise the rendering load to keep latency to a minimum.

Perceived delay can be better or worse than actual system latency. For example, in an AR system perceived delay might be greater than actual latency due to non-immediate marker detection.

Selected Steps

Of the several major steps that are part of the standard wound management procedure, the prototype focussed on the three central parts of the procedure: opening the dressing pack, cleaning the wound, and applying the new dressing. These steps encompass the common aseptic technique errors chosen to focus on (see Table 3.1) whilst minimising tracking challenges.

Omitted steps included opening and unpacking the wound dressing kit (containing sterile field sheet, tray, forceps, and swabs), preparing adhesive tape to attach the dressing to the wound, removing the old dressing from the wound, assessing the wound, the use of gloves (clean or sterile), and multiple hand washing steps. These are left to further work.

Size of the Wound's 'Clean' Area

Preliminary testing revealed that the swabs and forceps became contaminated from the area surrounding the wound (the patient's leg and the bed sheets) too easily. This is partly due to the two-dimensional nature of the simulated wound, as well as the limitation of swabs being pre-folded and therefore much larger than they would usually be relative to the size of the wound.

4.5 Summary

Ultimately, the aim of ARSterileSim is to help students develop an aseptic conscience: an awareness—a mental model—of what is sterile and what is not, and what causes contamination. This awareness needs to be at a subconscious level such that minimal concentration is required to maintain a sterile environment.

The design decisions were heavily influenced by the findings of the preliminary study, which identified common conceptual misunderstandings and subconscious errors that lead to a contaminated sterile field.

5 Evaluation Study

The overall aim of this research is to establish a rationale for using Augmented Reality in aseptic technique training as well as to identify design guidelines for future simulators. The evaluation study seeks to validate the findings of the preliminary study by assessing the face and content validity of the ARSterileSim prototype that was developed as a result.

5.1 Methodology

The assessment of face and content validity demands quantitative methods, however the exploratory aims call for a qualitative approach. A mixed methods design was therefore chosen to satisfy both requirements. The triangulation design convergence model, discussed in section 2.5.1, is ideally suited to this study as it allows both quantitative and qualitative data to be collected then interpreted together. Qualitative findings can help explain quantitative results, and quantitative results can help confirm and validate qualitative findings.

5.1.1 Research Questions (RQs)

The following research questions were established based on the overall aims of the research discussed in section 1.1 and the findings of the preliminary investigation. The first four research questions pertain to the prototype system specifically and aim to shed light on design guidelines for this new type of simulator. The fifth question seeks to go beyond this particular prototype implementation and asks about the validity of the approach in general. The research questions are as follows:

RQ1. How **accurate** is the prototype system in detecting errors in aseptic technique?
RQ2. Is the prototype system's level of **delay** acceptable?
RQ3. How effective is the **feedback** of the prototype system?
RQ4. How distracting were the physical **markers** used in the prototype system?

RQ5. What is the perceived **training potential** of an AR-based aseptic technique simulator?

In addition to these five research questions, the study aimed to allow room to explore additional topics to gain a deeper understanding of the research problem.

5.1.2 Participants

Educators involved in aseptic technique training from both academic and clinical contexts were recruited for this study. Participants were selected for their expertise and experience in teaching aseptic technique. As the aim was to gain a deep understanding of phenomena from experts, only a relatively small number of participants were required.

Educators in academia are focussed primarily on undergraduate nursing education, whereas those in a clinical setting are responsible for professional development of nurses at all experience levels. These differences in focus raise the question of whether any generalised differences exist between the two groups in terms of the data collected in this study. Participants were therefore classified accordingly.

Participants were asked several background questions regarding qualifications, training, and work and teaching experience to verify their 'expert' status. They were also asked where they were trained.

5.1.3 Data Collection Protocol

Prior to being interviewed, each participant was given approximately 15 minutes of experience with the prototype. First, a brief explanation of the system was given, then each participant was asked to attempt to clean and dress the simulated wound without making any aseptic technique errors. They were then encouraged to experiment by making deliberate errors and observing the system's response. This interaction was videoed primarily for the purpose of reviewing the prototype system's tracking performance. It also enabled participants' recollections of what happened to be compared against the recording where applicable. For example, if a participant had trouble recalling the cause of a contamination alert they received.

Likert scales were developed for RQs 1–5. A questionnaire was developed consisting of Likert items produced by this process, together with a set of open-ended questions to cover the remaining research questions. The questionnaire was administered in the form of a semi-structured interview lasting approximately 30 minutes. Participants were given a copy of the question-

Research Question	Likert Items in Questionnaire
1. Accuracy	A2, A4, A5, A13, B6
2. Delay	A3, A11
3. Feedback	A6, A7, A8, A12
4. Distraction of Markers	A9, A10, B7
5. Training Potential	B1, B2, B3, B4, B5

Table 5.1: Likert items associated with each Research Question.

naire and encouraged to respond to each question verbally as well as providing a written response. This promoted discussion of each topic and allowed the interviewer to ask follow-up and confirmatory questions. It also had the advantage of the collection of written responses summarising key points in participants' own words. Interviews were also audio-recorded for later review.

Some of the RQs inherently had more dimensions to explore than others, so the number of items per RQ is not uniform. The questionnaire is reproduced in Appendix A, and the association between Likert items and research questions is detailed in Table 5.1.

5.1.4 Quantitative Analysis

Likert item responses were coded from 1 to 5, where 1 = Strongly Disagree and 5 = Strongly Agree. Likert scale (RQ) results were calculated by taking the average of all Likert items for each scale. Mean and standard deviation, as well as histograms were used to summarise Likert data.

The Mann-Whitney test was used to determine whether responses from the two groups differed significantly. After confirming Likert scale data was approximately normal, Pearson's product-moment correlation co-efficient was used to identify correlations between Likert scales.

Microsoft Excel 2007 (Microsoft 2007) was used for preliminary analysis, Mann-Whitney tests were performed using the VassarStats.net online statistical calculator (VassarStats 2013), correlations were tested using the *Analyse-it Standard Edition 3.10 Excel plug-in* (Analyse-it 2013).

5.1.5 Qualitative Analysis

A generic qualitative analysis method was employed for analysing written and spoken responses to the Open Ended Questions (section C) as well as comments in relation to the Likert questions (sections A and B). Qualitative analysis was employed to address the research questions, but also to explore other

themes that emerged from the interviews. The process consisted of the following steps:

1. A general sense of the information was obtained through the interviews themselves, since a single researcher conducted all interviews over three consecutive days.
2. Participants' written responses were read and codes were assigned.
3. Initial themes were identified from the codes.
4. Interview recordings were reviewed in conjunction with each participant's questionnaire and instances of themes were noted as well as any new themes not present in the written responses. Key quotes were transcribed.
5. Themes and descriptions were arranged into a narrative (presented in the next section).
6. The data was interpreted to form conclusions and further work was considered (see Chapter 6).

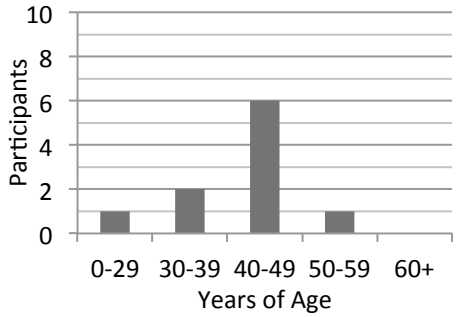
5.2 Results

The purpose of the evaluation study was to assess the face and content validity of the ARSterileSim prototype, and to use the prototype to stimulate further discussion with experts on this use of AR technology in teaching aseptic technique.

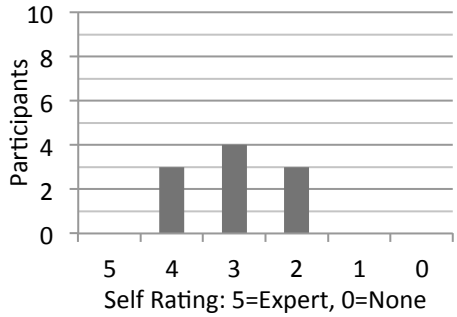
Five participants from the School of Nursing and Midwifery (Academic) and five from the Launceston Clinical School (Clinical) were recruited. Both schools are part of the University of Tasmania (UTAS) and are located at the UTAS Launceston campus and the Launceston General Hospital, respectively. Interviews were conducted over a three-day period in December 2012.

Due to the relatively small number of available local expert participants, a local convenience sample was used, which is consistent with qualitative studies, especially those focussed on experts. The geographical generalisability of findings is therefore limited, however there was some variety in where participants were trained and had previous experience. There was also a degree of self-selection, which may have resulted in participants who were more likely to have a positive attitude towards technology.

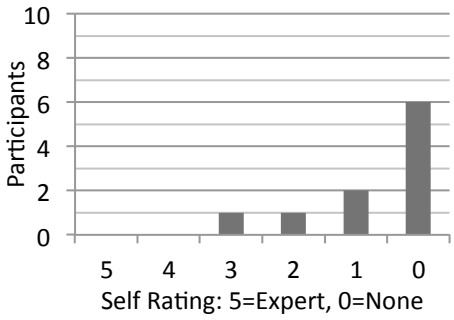
Demographic data can be seen in Figure 5.1. Participants were predominantly in the 40-49 year old age bracket and rated themselves moderately experienced with technology in general. Nine out of ten participants were female and were from a purely Nursing background, the remaining male being from a



(a) Age ranges of participants



(b) Experience with technology



(e) Experience with AR

Figure 5.1: Participant demographics

medical background. He was also one of the four participants who reported having had any previous experience with AR technology.

Participants each spent 8-12 minutes with the simulator. As they were experts, no non-deliberate errors were observed. Most participants required some encouragement to test the boundaries of the system after completing the initial wound dressing change procedure successfully. Participants with more experience with technology appeared to be more likely to explore what the system did and did not detect. The procedure is very standardised and there were no significant departures from the expected steps.

None of the participants showed any signs of disorientation regarding the mirror-image augmented view. This is likely because participants were looking at their hands and the objects they were manipulating directly most of the time, with only cursory glances toward the virtual mirror.

As part of the data validation process, it should be noted that one participant's (N02) responses to questions A4 and A5 were omitted from analysis due to confusion regarding the scope and negative phrasing of the questions. Discussion during the interview revealed that this participant's responses did not match their actual views given the intended meaning of the questions. Similar discussion with other participants confirmed their correct interpretation. It

was requested that they change their answer but they insisted on answering according to their original interpretation leaving the researchers no choice but to exclude those data points.

Results of the five Likert scales created to address the five research questions are summarised (by mean and standard deviation) in Table 5.2 and illustrated in Figure 5.2. As mean and standard deviation alone do not give a complete picture of response patterns, histograms are also presented in Figure 5.3. In general, participants agreed that the prototype gave effective feedback (RQ3), and that the fundamental approach had great training potential (RQ5). Any delay noticed by participants was deemed acceptable (RQ2), but participants were divided on the tracking accuracy (RQ1) and the issue of distractive physical markers (RQ4). There was no significant difference ($p<0.05$) between the responses of clinical and academic groups to any of the Likert scale questions. Full results of the Mann-Whitney tests are shown in Table 5.3.

For completeness, responses for each individual Likert item are also presented in Figure 5.4. Since these are individual Likert items, the data is considered ordinal, therefore a box plot has been employed using a five-number-summary representation.

Pearson's product-moment correlation co-efficient was used to test each RQ dataset against every other RQ dataset for correlations. Only one significant correlation was found ($P<0.05$), which was between RQ1 and RQ4 (see 5.2.4). Pearson's was also cautiously used to consider possible correlations between individual Likert items. Only those questions that were clearly parametric were considered. Correlations were found between experience with technology and A4.

Each research question will now be considered in detail, drawing quantitative and qualitative data together to construct an in-depth understanding of results.

5.2.1 RQ1: How accurate is the prototype system in detecting errors in aseptic technique?

Opinions regarding the prototype system's ability to accurately detect aseptic technique errors were mixed, with Likert scale results ranging from 1.8 (just below 'Disagree') to 3.8 (just below 'Agree') with a mean of 3.2 ('Neutral'). Closer inspection of the Likert items comprising this scale reveals that responses were often at extremes, with participants strongly agreeing or disagreeing. This is largely due to the fact that some participants experienced false-positive contamination errors and some did not. For example, one participant described the markers as "clunky," and "not entirely accurate" (N02),

Research Question	Clinical (*n* = 5)	Academic (*n* = 5)	Total
1. Tracking is Accurate	3.3 ± 1.0	3.1 ± 0.7	3.2 ± 0.8
2. Delay is Acceptable	4.2 ± 0.3	4.3 ± 0.4	4.3 ± 0.4
3. Feedback is Effective	4.5 ± 0.4	4.4 ± 0.6	4.4 ± 0.5
4. Markers Not Distracting	3.1 ± 0.7	3.3 ± 0.8	3.2 ± 0.7
5. Great Training Potential	4.6 ± 0.4	4.9 ± 0.3	4.7 ± 0.3

Table 5.2: Likert Scale Results by Group (mean ± SD). No significant differences between the two groups (P < .05).

Research Question	Mann-Whitney Test Results
1. Accuracy	U(8) = 12.5, Z = 0.1044, 0.46017
2. Delay	U(8) = 11.5, Z = -0.1044, 0.46017
3. Feedback	U(8) = 11, Z = 0.2089, 0.41683
4. Distraction of Markers	U(8) = 10, Z = -0.4178, 0.33724
5. Training Potential	U(8) = 5, Z = -1.4623, 0.07215

Table 5.3: No significant difference (p<0.05) between clinical and academic groups.

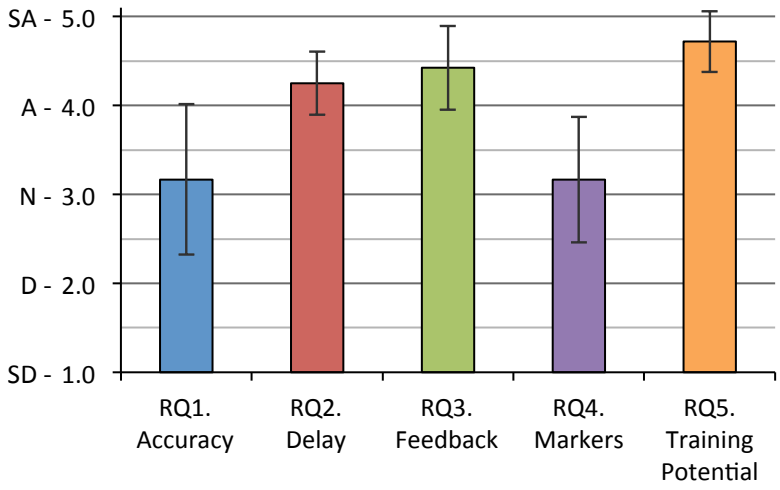
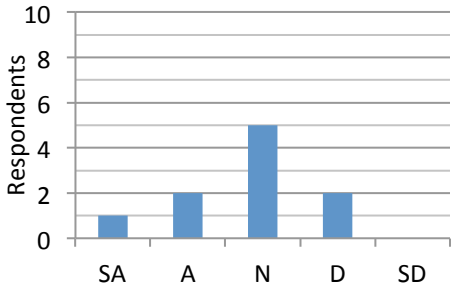


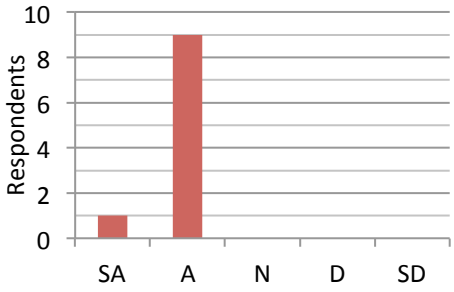
Figure 5.2: Likert Scale Total Means. Error bars show standard deviation.
(SA = Strongly Agree, A = Agree, N = Neutral, D = Disagree, SD = Strongly Disagree)

while another commented, "there was no error detected by the system until deliberately done" (N03).

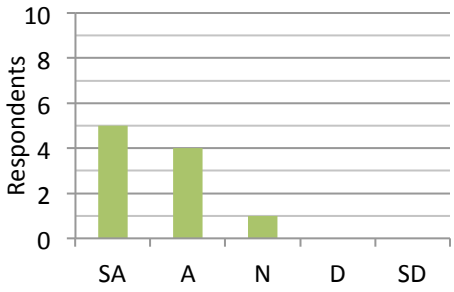
Two main issues relating to aseptic technique error detection were identified: tracking accuracy, and the contamination rules of the simulation.



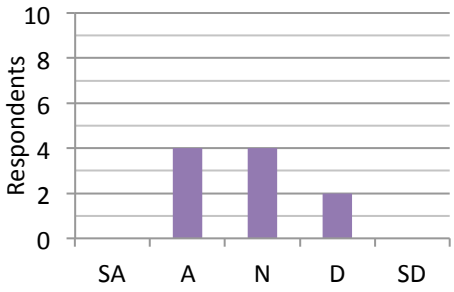
(a) RQ1: The prototype's aseptic technique tracking is accurate.



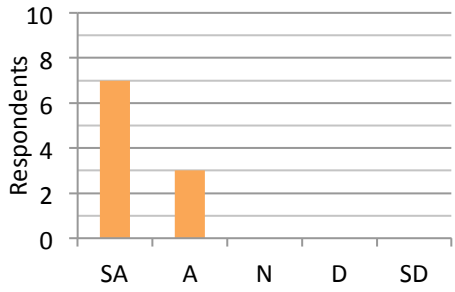
(b) RQ2: The system's delay is acceptable.



(c) RQ3: The feedback provided by the system is effective.



(d) RQ4: The markers are not distracting.



(e) RQ5: An AR system like this has great training potential.

Figure 5.3: Histograms of Likert Scale Results
(SA = Strongly Agree, A = Agree, N = Neutral, D = Disagree, SD = Strongly Disagree)

Tracking Accuracy

The Vuforia tracking system is generally very successful at maintaining tracking under ideal conditions, however in certain circumstances tracking can be lost. Tracking loss can cause brief but significant errors in the perceived position of markers, leading to false-positive contamination events.

For example, if a swab is erroneously perceived to be located outside the sterile field, even for a split second, the system will mark the swab as contaminat-

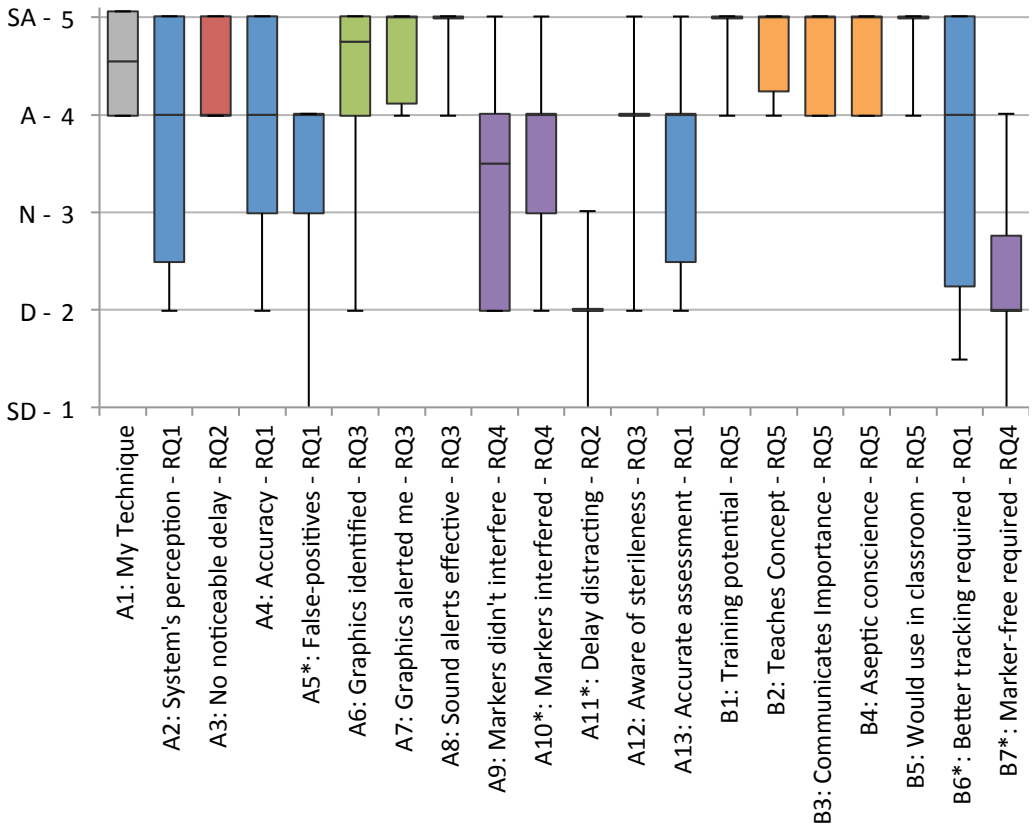


Figure 5.4: Individual Likert Item Responses

ed. This was frustrating for participants when it occurred, especially as the source of contamination was usually unclear.

Some participants clearly understood that the system needed a clear view of markers and took care to minimise occlusions and face markers towards the camera, and to confirm that the markers being manipulated were being tracked. Other participants were more prone to manipulating objects in ways that create unfavourable conditions and experienced more frequent tracking loss which resulted in a higher rate of false positive contamination errors. Unfavourable conditions include, for example, partial occlusion of markers, or markers positioned at a sharp angle with respect to the camera plane. These participants experienced up to half a dozen discrete false-positive contamination events requiring the system to be reset so they could continue.

Lighting conditions likely also affected the tracking quality between participants as the study was conducted in two different rooms, and the position of the sun changed the lighting in the room through the course of each day.

Most participants commented on the limitations of the tracking quality to some degree, with four out of ten identifying tracking accuracy as an area requiring improvement. Those with more experience with technology tended to rate the tracking system's accuracy more poorly, probably these users were more likely to pay attention to whether objects were being accurately tracked or not, and took care to orient markers such that the system had a clear view of them. Those with less experience with technology generally felt the system was able to track everything accurately, though this may have been influenced by assumptions regarding the ability of the system rather than actual observations.

There was a possible negative correlation between self-reported level of experience with technology and Likert item A4: "The system always accurately detected when contamination occurred," $r = -0.727$, $n = 9$, $p = 0.0172$, however this result carries limited weight due to the small sample size and technically ordinal (not interval) dataset. This correlation would be an interesting subject of a future study.

Participants were divided on whether better tracking performance would be required before ARSterileSim became a useful teaching tool (question B6), with six saying it would need to be better, three saying it would be useful as it is, and one neutral. Those who felt it would be useful as-is saw the system as being a beneficial component of teaching aseptic technique within the context of traditional teaching methods around the aspects that ARSterileSim do not cover, such as setting up, assessing the wound, pack up, and documentation.

Contamination Rules

Improving tracking accuracy is a technical challenge requiring a technical solution, but addressing incorrect contamination rules requires a deeper understanding of the theory behind correct aseptic technique. Participants identified several areas needing improvement.

Although a known limitation of this first prototype, the lack of hand or glove tracking was the number one issue cited by participants. Hand hygiene and subconscious touches were commonly mentioned as important sources of contamination missing from the prototype. Participant N04 had the following to say regarding subconscious touches:

> *In my experience, that's where most contamination comes from because for some reason students don't see themselves as a potential contaminant.*

The choice of sterile or non-sterile gloves has aseptic technique implications on the rest of the procedure, so this is also a crucial component, as is the sequencing of deciding when to put on a particular pair of gloves, so participants felt this needed to be included too.

One issue was the distance from the edge of the sterile field sheet that should be considered contaminated. The prototype was coded with only a centimetre or two for this safety buffer, however it was found that a 'couple of inches' should be considered contaminated due to the way the pack is (usually) opened.

The issue of avoiding 'fallout' from non-sterile objects entering the space above the sterile field was also raised. As discussed in the findings of the preliminary study, this rule was left out due to the requirement that some items be allowed to enter this space, albeit held as high as practicable. The saline pack is the main example of this along with the dressing pack. The latter being an interesting case, as a small number of participants took care to hold the dressing pack off to the side of the sterile field sheet, flipping the dressing out onto the sheet without any risk of fallout. Most did not do this, however, so the question of how necessary this is remains. One possibility for a future version is to only allow specific non-sterile objects into this safe zone above the sterile field.

Several participants commented on another known limitation: the size of the wound's 'clean' area was too large. As discussed in section 4.4.2, this was made extra large to combat the false-positive contamination errors that were occurring due to a combination of factors, including the wound being represented by a two-dimensional image, and the swabs being non-foldable and therefore too large relative to the wound.

An additional related finding is to do with the technique required for cleaning the wound itself. Each swab should wipe the wound once only before being discarded, and each wipe should be in an inside-to-outside direction. The reason for this is that the patient's skin surrounding the wound is not part of the wound field as it can harbour microbes that should not be introduced to the wound. The current representation of sterile and non-sterile areas using colour-coded cube-shaped zones is not a good fit for this requirement. One participant commented, however, that they would prefer to see a more realistic representation of microbes as small dots that smear and spread as objects touch each other, much like the look of Glo Germ (Glo Germ 2012).

5.2.2 RQ2: Is the prototype system's level of delay acceptable?

The frame rate of the prototype running on the iPad 2 was nominally 30 frames per second, but could drop to 20-25 frames per second when ImageTarget tracking was lost. This variation is most likely due to the higher processing requirements of detecting a target from scratch compared to maintaining tracking of a target whose position in the previous frame is known.

End-to-end system latency was measured as being approximately 160ms, however there can be added perceived delay due to markers not being detected immediately. Motion blur, in particular, can cause a marker to not be detected until it has been relatively still for several frames.

All participants agreed, however, that there was no noticeable delay in the system, and that the level of delay was therefore very much acceptable.

The virtual mirror configuration likely affords more tolerance for delay than other AR display techniques, particularly HMDs. There was, in fact, considerably less delay in the final prototype system than in earlier iterations. Hence, it turned out to be much less of an issue than expected.

5.2.3 RQ3: How effective is the feedback of the prototype system?

All participants responded positively towards ARSterileSim's feedback mechanisms, with a mean Likert scale response of 4.4 (between 'Agree' and 'Strongly Agree'). Participants were asked about the graphics and auditory cues, and several additional themes relating to feedback emerged from the qualitative analysis of interviews: participants really liked that the feedback was *instantaneous* and also that it was *objective*. The virtual mirror style of AR interface was also liked.

Graphics and Audio

The graphics used were generally judged to be a clear and sufficient representation of sterile and non-sterile conditions, with relatively few suggestions for improvement. A common theme was the idea that students find the concept of sterile and non-sterile objects quite abstract and that ARSterileSim's visualisation made this concept much easier for them to grasp. In the words of one participant (N04):

> *"At the moment it's something they can't see. ... I suppose it's like trying to explain an abstract concept to a child when they can't actually see it. You're telling them, '[you did contaminate it]', but because they can't see bacteria, [they say] 'no I didn't', [but actually] well, yeah, you did."*

Another participant (L04) reacted with, "Wow, what a bizarre concept! It's really weird to *see* it like this." This and other similar reactions suggest that the visualisation provided by ARSterileSim was a good fit for the mental model of the sterile field held by the experts, but also that each expert had developed this mental model in their own mind without visual aid.

The value of the visualisation for students is also demonstrated by the following thought from another participant (L01):

> *"Yes, I think [the system]* would *assist in helping students understand the concept of a sterile field, instead of trying to get them to* imagine *a border around the sterile field! Again, visual cues assist greatly with this."*

The audio alerts were also valued for their ability to interrupt the user when a breach of asepsis occurred, even when the user's attention was not on the screen. The Likert item asking about the value of the sound effects (question A8) received nearly all 'strongly agree' responses.

Suggestions for improving feedback included replacing the 'red block' metaphor with a more literal representation of microbes using clusters of small red dots, as discussed above.

Another suggestion from several participants was that clearer feedback on whether tracking was active for each marker would be helpful, given the system's tracking accuracy limitations. Sterile items in particular were only displayed with a very subtle blue shading which was difficult to see in some circumstances.

A suggestion for audio feedback was using voice output to indicate what became contaminated and what caused the contamination. For example, "forceps contaminated from sterile field perimeter," or, "sterile field contaminated from saline pack." This was prompted by occasions where an audio alert would occur, the user would look up at the screen and notice that something had become contaminated, but the source of the contamination was unclear.

Another related suggestion was the ability to produce a report at the end listing the contamination events that had occurred during the session, possibly including screenshots of key moments.

Instant Feedback

The value of instant feedback was identified as a strong theme. In assessments, feedback is often not given until the procedure is completed, at which point the negative behaviour has already been reinforced. As articulated by participant L01:

> *The constant visual... and auditory feedback if contamination has occurred [means] you're not actually reinforcing inappropriate practice by getting to the end of an assessment and saying, 'you did A, B and C [wrong],' you actually stop at the point of contamination and say 'right, you've got to start again.'*

In clinical settings there is no feedback at all, and, as discussed in the literature review in section 2.1.1, it is difficult to trace infections back to a cause as there are usually many potential sources of infection. Participant L04 had this to say:

> *One of the things we struggle with so often is that germs are invisible, and you get no feedback about whether you've introduced germs into something or not, because if you don't do something properly aseptically, it's three days later when the patient gets sick and you're not there anymore. Whereas this, they go 'oh no! I can't do that [because it's red].'*

Objective Feedback

The value of objective feedback was another strong theme identified from the interviews. At UTAS, SNM classrooms typically have 25 students to one teacher, so staff are unable to observe all students simultaneously. Students are observed by their peers, but not only are their peers not experts, but, "friends probably aren't going to say, 'you got that wrong,' or they'll say, 'oh, it's ok, keep going.'" (N04)

Whether being watched by their peers in the classroom, or by teachers in formal assessments, students frequently question allegations of aseptic technique error, particularly when it comes to subconscious errors. Participants really liked the idea of a system that assesses aseptic technique objectively. Participant L05 had this to say on the matter:

> *The most important reason that I would use a system like this is the very clear signal that a student gets that they have contaminated, because it* is *difficult to watch people undertaking a skill. ... You know, they'll say, 'she said I contaminated that and I didn't,' but this takes away all of the subjectivity. It's there; it's clear. You've just plonked [a non-sterile object] there and now there's a red square and a signal to shout at you. ... It's good learning, so that's the absolutely best part about it.*

The Virtual Mirror Approach

A number of different approaches to AR display technologies were discussed in the literature review in section 2.3.3. A few participants had seen examples

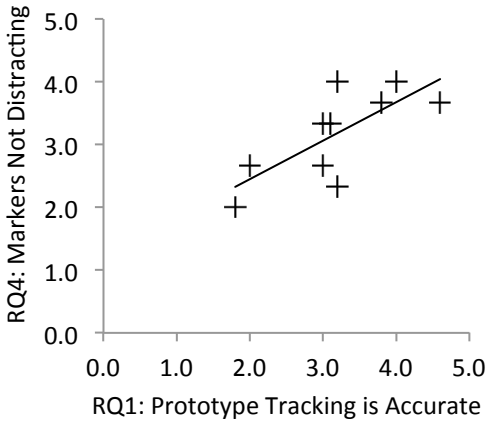


Figure 5.5: Correlation between RQ1 and RQ4. r = 0.734, n = 10, p = 0.0157.

of AR using other approaches, particularly HMDs. Several commented that the virtual mirror was a much better approach for this project, citing the awkwardness of wearing a HMD, and the suitability of the virtual mirror setup to a group of students gathered around a station. There was consensus that the mirror metaphor was effective and intuitive, and that it was not necessary for augmentations to appear on objects in real space (as opposed to on the virtual mirror) for the system's feedback to be effectively communicated.

One participant commented that they had come in to the research session expecting the ARSterileSim prototype to use a HMD, and that they had low expectations regarding the usability of the system as a result. However, the virtual mirror approach exceeded their expectations, and seemed much more suited to use in the classroom than HMDs.

5.2.4 RQ4: How distracting were the physical markers used in the prototype system?

Participants were split on how distracting the markers were. Figure 5.5 shows a significant positive correlation, r = 0.734, n = 10, p = 0.0157, between attitude towards the tracking markers (RQ4) and perception of tracking system accuracy (RQ1). In other words, participants that experienced difficulty with tracking accuracy (experiencing false-positive contamination errors, for example) tended to have a poorer view of the interference of markers. This suggests that users might be more likely to tolerate large markers so long as tracking quality was improved.

On the other hand, several participants commented that the presence of tracking markers forced them to change their technique from the way they would normally do things in order to accommodate the physical constraints the markers imposed. This suggests potential for negative transfer: technique

learned while using ARSterileSim may not be ideal technique when not constrained by attached physical markers.

The primary culprit was the forceps, with six out of ten participants specifically asking if the forceps' markers could be smaller. The forceps were the only tracked objects where the markers had to be attached sticking out from the object itself, which, "impeded dexterity." The forceps' markers also frequently occluded markers on other objects that were being picked up, such as swabs, preventing accurate tracking and leading to many of the false-positive contamination errors that were experienced.

The swabs were the other main instance where participants felt markers got in the way, as usually swabs would be folded, scrunched up, or even wrapped around the tips of the forceps, depending on the characteristics of the wound being cleaned. Participants commented that for the size of the wound used in the prototype, the pre-folded size of the swabs was much too large. As mentioned in relation to RQ1 above, this was one of the primary causes of false-positive contamination errors during the interviews. By contrast, the dressing does not need to be folded and is naturally quite rigid anyway, so attaching markers to it made little difference to how it was handled.

Would the System need to be Marker-Free?

Despite the desire for smaller markers, most participants felt that marker-free tracking, though ideal, would not be required in order for it to be a useful teaching tool (question B7). Again, 'useful,' not for teaching every aspect of wound management, but for teaching the general concept of aseptic technique within the context of traditional teaching around other aspects of wound care.

One participant (L05) commented that the presence of markers reminded the user they were being tracked and that they would therefore be more mindful of their technique during training. This has potential implications on the transfer of learned skills back to a clinical setting where there are no markers and they are not being tracked. Of course, this is a challenge for any training exercise as students naturally differentiate between training and the real thing.

5.2.5 RQ5: What is the perceived training potential of the technology generally?

There was strong positive sentiment towards the general approach, with most participants strongly agreeing that the system had great training potential. The 'training potential' Likert scale scored a mean of 4.7, out of a maximum of 5.0.

One participant (N05), when asked what they like about the system, responded with, "What do I like about it? A lot! I like the overall concept; I like the idea."

Another (N04), said, "I love the idea, I think the idea is just amazing and probably would revolutionise the way we taught [aseptic technique]."

The perceived training potential revolved around the feedback the system provides. Participant N01 made the following comment:

> *Some people like the doing but [this system] is more than doing because you're actually getting feedback. [Otherwise] they can just keep doing it but you wouldn't know; you can keep doing the wrong thing over and over again.*

This was a sentiment echoed by many other participants. For example, N05:

> *The fear, for me, is always that [students] practise a skill in a poor manner until they're really 'good' at it.*

and N04:

> *If you're not with them every time; the time you see them do it might be great, until they see how someone else does it and they think that looks better and they end up practising and practising until they're really good at doing it wrong.*

As mentioned in relation to RQ3, above, which discusses the specifics of the system's feedback, the instantaneous and objective nature of ARSterileSim's feedback was highly valued.

Participants were asked about the system's ability to aid the teaching of several aspects of aseptic technique: the concept of a sterile field, the importance of maintaining a sterile field, and the development of an aseptic conscience.

The Concept of a Sterile Field

Participants all agreed that the system has great potential for helping students understand the concept of a sterile field. One aspect of this is helping students understand the boundaries and borders of the sterile field. Participant N05 explained it thus:

> *Absolutely it would help them understand the concept of a sterile field... For instance, the edges of the sterile field: What is sterile? Which parts of what? ... Then when they move on to the patient, is it just the wound? How far around the wound? Is it [including] nightdress and pyjamas? Is*

> *it their clothes? Is it the bed? So, how much of what is sterile? And I think [the system] really helps with that.*

Participants also felt the system excelled in teaching about the way contamination easily spreads in a sterile field, sometimes called the 'snowball' effect. The system clearly illustrates how a seemingly small error at the beginning of a procedure can easily propagate to the point that just about everything is contaminated.

Participant N02 called this "the flow-on spread of contamination," saying, "cause you might think, 'oh, I touched that, whoops,' but then if you keep going, ..." implying that it quickly becomes evident that a student cannot keep going while maintaining asepsis.

Another participant (L02) commented that, "it spreads so quick once [you contaminate something], you almost end up with 100% [contamination] don't you!" When asked if the system simulates the spread of contamination too easily, she responded, "but you need it to demonstrate that because that *is* the potential, and if you reduce that because you think it's a bit too much, I would imagine you'd lose the impact of contaminating."

The Importance of Maintaining a Sterile Field and Aseptic Conscience

Two themes relating to the importance of maintaining a sterile field were identified. The first, which has already been discussed above, is the idea that even a 'small' breach, if not recovered from adequately, can lead to widespread contamination of the sterile field. This is an important concept for students to grasp, as without it they have no reason to be diligent in their aseptic technique during all stages of a procedure. As mentioned above, participants agreed that the prototype is well suited to teaching this aspect.

The more important aspect of the importance of maintaining a sterile field relates to risk to the patient: Students need an awareness of the implications for the patient should infection occur as a result of a breach. There was consensus that this was not currently covered by ARSterileSim. In the words of one participant (N03):

> *They get the alert and it tells them when they've contaminated something, ... but there's no emotional thing attached to it. ... There's no consequence of it. You do it and you make a few mistakes and a red light comes on. Does that say to me, 'that puts my patient at risk'?*

The importance of maintaining a sterile field is encapsulated in the idea of aseptic conscience (sometimes 'surgical conscience'). An aseptic conscience is

defined in the literature as an awareness of sterile and non-sterile items and the ability to take corrective action should contamination occur, underpinned by the ethic that nurses should do the patient no harm (Lewis 2009). Note that there are two major elements mentioned here: one being about awareness and ability, the other being about ethic.

One participant described aseptic conscience as "an ethical obligation to take care of people you're doing dangerous things to," giving the following example:

> *For instance, if I'm pouring fluids for someone who's [working] in a sterile field... I open it... and I think I touch it. I'm not sure I've touched it, but I* think *I've touched it. I know that I have to discard [it] ... and start again, because my surgical conscience tells me that* thinking *I didn't touch it isn't quite good enough – I have to* know *I didn't touch it.*

If students do not understand the potential consequences of infection, they have no reason to be diligent in their aseptic technique. Truly internalising the implications of infection comes with experience, which is something that students do not have yet, as one participant (N04) explained:

> *In practice, we call it having a surgical conscience, [which means] if you muck something up you're going to start again, whereas [students] haven't developed that because they don't understand the implications of that yet, so you're teaching students without a context. You know, [I] try to explain to students that if you muck this up it's going to have huge implications for a patient. At the very least they could get an infection. At the other end of the spectrum they could die because of something that you did. But trying to explain that to a first or second year student who ... hasn't been out there and seen the implications of an infection, ... they just think, 'oh well, we'll just give the patient some antibiotics and they'll be fine.' They don't understand that the patient could lose their leg or whatever. ... and that's something I really struggle with [teaching].*

The general feeling was that ARSterileSim does not currently cover this motivation aspect of the importance of maintaining a sterile field. Some participants felt that this could simply be considered outside the scope of the system and could be taught separately alongside the AR system.

One suggestion for incorporating feedback on consequences for the patient was to display messages at the end of the procedure regarding patient outcomes:

> *It needs like an error message with it [when you contaminate]. Maybe, 'Mrs Jones just got an infection in her total hip replacement which means three months of hospitalisation, antibiotics, ... potentially she might need to have her joint replacement removed, reducing her mobility.'*

Transfer to Practice

An important question in simulation, and the learning of skills in general, is whether skills learned transfer from the simulation setting to clinical practice. As discussed in section 4.4, the main goal of ARSterileSim was to enable students to build a mental model of a sterile environment, such that when the system is taken away students are able to essentially run the simulation in their head, imagining the visual and auditory feedback, giving them an instinctive awareness of the sterile environment.

Although additional study would be required to properly assess this phenomenon, unprompted comments made by two participants provide initial evidence to suggest that the prototype might be successful in this aim, at least in terms of the audio feedback.

One comment from participant L02 in relation to question B2 was:

> *I reckon they'd have the mental buzzers going off in their head if they've done it enough times and did it wrong in practice.*

A similar comment was made by participant L04 in relation to question C7:

> *When they do it wrong in the ward, they'll expect a buzzer to sound!*

5.2.6 Other findings

Several other themes emerged in the interviews that did not fit in any of the above categories. They are discussed in this section.

Benefits over other forms of Computer-Aided Instruction

A specific question was asked about the perceived benefits of AR technology for aseptic technique training over more traditional mouse-and-keyboard or touch-screen approaches. The responses were all along the same lines, with participants citing the tangible, tactile nature of practising with real equipment, enabling learning of practical skills to take place in a realistic context in the vein of simulation. This practical aspect is completely absent from purely digital teaching aids.

One participant described how a five-year-old they knew was doing knee reconstructions online by clicking on the right things in the right order. They

pointed out that this child's ability to complete knee reconstructions on a computer screen does not necessarily translate to the practical skills necessary to attempt such a procedure!

Participant (N05) summed up this issue well:

> *Oh loads [of benefits], because they're actually undertaking the practical skill. They're using their hands, ... we can talk and demonstrate as much as we want; they can look at things on the computer, ... [but] it's only when they're actually physically undertaking the skill can you see [that they understand].*
>
> *For example, I've seen people describe to patients how to use asthma inhalers, but if you don't show them and* see *them do it, you see all sorts of weird and wonderful things. I saw a patient once who ... sprayed the inhaler over their shoulder, [because that's how it was demonstrated to them].*

Cost and Portability

Many participants commented on the portability and low cost of the hardware needed for the prototype system. The low cost placed the technology within reach, as opposed to a several thousand-dollar system that would be unattainable for most. The portability of the system was considered a key consideration for whether they would be likely to use it in the classroom.

Application to Other Procedures

Many participants saw applications beyond the wound management area demonstrated. Suggestions included catheterisation, cannulation, insertion of central lines, and even the entire operating room. Essentially, any procedure that is invasive and punctures the skin, particularly when instruments are left in for any period of time. In short, any procedure where aseptic technique is required was seen as a candidate.

5.3 Summary

The prototype was well received by staff in academic and clinical contexts equally. System delay was felt to be negligible, the visual and auditory feedback mechanisms were praised, and the future potential of AR-based aseptic technique training was felt to be very promising, for correcting conceptual misunderstandings as well as subconscious errors.

The simulator was considered successful at communicating the importance of not allowing even 'small' errors in aseptic technique due to the snowball effect this has in spreading contamination to other objects.

The tangible interaction afforded by the simulator was felt to be of great benefit, as students get to practise actually performing tasks using real equipment. Participants liked the virtual mirror display configuration finding it intuitive, and preferable to the idea of putting on a HMD.

Weaknesses were related primarily to tracking inadequacies. The tracking quality was considered adequate to poor and some of the markers, particularly the ones attached to the forceps, interfered with the prescribed wound care task. Additionally, the absence of hand or glove tracking was considered a crucial missing feature.

Despite these limitations, three out of ten participants felt the simulator would be beneficial to students even as it was, with everyone indicating that they would like to use a similar simulator in their own teaching.

Overall, evidence has been shown that clearly demonstrates face validity of the approach to AR-based aseptic technique training. With the exception of hand tracking, content validity within the defined parameters of the prototype (i.e. selected wound care steps) has also been demonstrated.

6 Conclusion

The purpose of this research was to establish a rationale for using Augmented Reality (AR) technology to create a sterile environment simulator for aseptic technique training, and to evaluate a prototype of such a system. A Mixed Methods approach was used, with a qualitative preliminary study informing the design of the second, main study, which itself employed qualitative and quantitative methods.

First, a preliminary investigation was conducted including informal interviews with academic staff involved in undergraduate aseptic technique training, and an observational study of first-year nursing students attempting aseptic technique for the first time in the context of wound management. The preliminary investigation identified key challenges in aseptic technique training and common errors made by students.

A prototype AR system, *ARSterileSim*, was developed based on the findings of the preliminary study. The prototype is designed to simulate a sterile environment, displaying the normally invisible spread of contamination, allowing students to see the effects of their actions. Feedback is an essential component of the experiential learning cycle, but traditional aseptic technique training methods are unable to provide adequate feedback due to limited availability of qualified instructors.

The evaluation study assessed the face and content validity of the ARSterileSim prototype and explored general issues related to the use of AR in teaching aseptic technique. Ten experts in aseptic technique training—five each from academic and clinical backgrounds—were given time to use the prototype system followed by an interviewer-administered questionnaire. This format allowed both quantitative Likert scale data and qualitative data from interviews to be collected. The two types of data were analysed together, following a mixed methods triangulation design: qualitative findings were able to confirm and explain quantitative results.

6.1 ARSterileSim Prototype System

ARSterileSim was designed based on the findings of the preliminary study. This section outlines several key findings from the study and how they affected the design of the system.

When practising aseptic technique in the classroom, students commonly made errors stemming from an inaccurate or incomplete understanding of the boundaries of the sterile field. For example, placing sterile items too close to the edge of the sterile field sheet. The prototype was therefore designed to give clear visual feedback as to sterile and contaminated areas by colour-coding them blue and red respectively.

Students also frequently made subconscious errors such as scratching an itch or touching their hair with sterile gloves on. To ensure errors were noticed immediately an audio alert was employed.

A key concept for students to internalise is the 'snowball' effect: the idea that one small contamination error will lead to further contamination if left unchecked. The prototype helps students with this by demonstrating how readily contamination propagates from object to object as they come in contact with one another.

6.2 Key Findings

Participants universally agreed that the approach had merit and warrants further study. Despite some deficiencies, all participants agreed that the concept of ARSterileSim has great potential for aseptic technique training, many saying that they would be very interested in using it as part of their own teaching. Participants responded very positively to both the visual and auditory feedback provided by the prototype. In particular, they liked that the feedback was instantaneous and objective. The virtual mirror configuration of AR display was thought to be intuitive and an appropriate choice for this application compared with other AR display techniques, such as HMDs.

Participants identified several areas where the ARSterileSim prototype needed improvement. The tracking accuracy was generally felt to be insufficient, though some participants felt the system would be a useful teaching tool as-is. The size and placement of physical markers on some objects (particularly the forceps and swabs) were found to be cumbersome, restricting dexterity and impeding the reality of the simulation, which potentially reduces transfer of learning to clinical practice. Hand tracking was identified as an important

component that was missing from the prototype, as students often cause contamination through subconscious touching of their own body.

Another significant theme was the importance of the tangible nature of the simulator made possible by AR technology, compared with a computer-based implementation, in theory enabling strong transfer of learning to clinical practice.

6.3 Lessons Learned

A number of lessons can be learnt from this research for the benefit of others carrying out similar work in the future. These centre around tracking reliability and hand tracking.

Tracking reliability is an important consideration for any AR application, however it is particularly crucial in an application such as ARSterileSim, where tangible interaction concepts such as spatial proximity are used to affect the state of virtual objects. Unreliable tracking in a visual output-only AR system is frustrating, but in ARSterileSim this leads to false positive contamination errors, leaving novice users uncertain as to whether they made an error or not, and requiring the simulation to be restarted. A future implementation of this kind requires dramatically improved tracking reliability.

Hand tracking was identified as a crucial missing feature of the prototype, as students' hands are a primary contamination vector. As discussed in the literature review (section 2.3.1), active infrared depth sensors such as the Kinect offer a promising option for tracking hands, bodies, and even arbitrary unmarked objects. The Kinect is discussed in more detail in the next section.

6.4 Further Work

This research has presented evidence that an augmented reality simulated sterile environment has face validity as an aseptic technique teaching aid, and that content validity of the ARSterileSim prototype has also been achieved within specific known limitations, as defined in section 4.4.3. This section identifies questions that arise from the research that are recommended as topics for further work.

6.4.1 Improvements to the Prototype Design

The ARSterileSim prototype took many design cues from the results of the preliminary study, however there is plenty of room for the examination of alternative design choices.

This first prototype excluded certain steps of the wound care procedure. Future versions should aim to incorporate more elements with an ultimate goal of realistically incorporating the whole procedure.

The visual feedback design can be further refined, making use of alternative colour schemes or animations. As suggested by one participant, a more realistic visualisation of microorganisms such as you would expect to see through a microscope could be employed as an alternative to the coloured blocks metaphor used by ARSterileSim.

The use of audio feedback can be explored further. Alternative sound effects could perform better, or could be varied in order to communicate more information such as which object was contaminated or what the source of contamination was. Another participant suggested the use of voice synthesis to speak directly to the user, telling them what has been contaminated. A proximity warning sound could increase in volume according to how close contamination is to occurring, allowing users to respond accordingly and avoid contamination.

While the Virtual Mirror metaphor worked well for participants, it would be interesting to compare this to prototypes making use of projector or HMD-based AR display methods. These approaches place augmentations directly in the user's line-of-sight which could increase engagement and therefore transfer of learning. As HMD technology improves it will undoubtedly become less cumbersome and a more viable option so should be reconsidered in the future.

6.4.2 Tracking Improvements

Tracking reliability was clearly detrimental to the overall usefulness of the simulator. Improvements in hardware and available AR SDK technology will obviously improve this, however alternatives to purely vision-based tracking should also be considered.

Active infrared depth sensors such as the Kinect have considerable potential for application in this domain, either as a complete replacement, or more likely in addition to vision-based tracking methods. A major benefit of this sensing technology is increased generalisability to tracking arbitrary objects. This allows any unrecognised object to be a potential source of contamination, such as room geometry and arbitrary body parts and clothing. Challenges include segmenting objects when in close proximity and tracking discrete objects between frames. Visual cues such as markers or colour coding could assist with this.

6.4.3 Establishing Stronger Validity

Having assessed the prototype's face and content validity, the next step would be to conduct a study examining construct validity. Construct validity measures the degree to which the simulator can discriminate between users of different skill levels. One way to measure this would involve testing a new prototype with beginners and experts and comparing their performance in the simulator with known skill levels, or the results of an existing previously validated testing method.

The most powerful type of validity is concurrent validity, which tests whether skills learned in the simulator are transferred to clinical practice. This is a crucial type of validity as it is the only type that actually confirms that a simulator makes any difference to patients. A randomised controlled trial is the usual method for measuring concurrent validity. A suggested protocol for testing concurrent validity of an AR sterile environment simulator is as follows:

It is suggested that first year Nursing students be recruited and randomly assigned to two groups: a control group and a treatment group. Both groups would first receive traditional aseptic technique instruction in the classroom. The treatment group would then spend a certain amount of time practising aseptic technique with the simulator. The control group would be asked to spend an equivalent amount of time practising without the simulator. Both groups would then be assessed for correct aseptic technique by qualified staff members. A written questionnaire could also be used to test conceptual understanding of aseptic technique concepts. A Mann-Whitney test could then be used to test for significant differences in student performance between the two groups. Ideally, a pre-treatment assessment could also be used to establish a baseline, however if participants with prior aseptic technique experience are excluded, and the sample size is large enough, this should not be necessary.

In addition to establishing the validity of a simulator unto itself, it would also be valuable to validate the technology against other more traditional training methods. Otherwise a simulator may simply be better than a poor teaching method, but not be superior to some other approach.

6.4.4 Other Applications and Features

Aseptic technique is required for any invasive procedure in nursing or medicine, such as catheterisation, cannulation, or surgical procedures. As one participant with a medical background pointed out, in the surgical operating room the risks of infection are even more serious, as an infection in an internal organ poses far greater risk to a patient than an infected wound. This concept

of an AR simulated sterile environment can conceivably be applied to any other invasive procedure. It would primarily be a matter of planning how to track the relevant objects involved.

On the other hand, it may be the case that once the concept of aseptic technique is internalised, it might not need to be re-learnt for each specific procedure. This in itself would make for an interesting study.

Another important point raised by several staff members was the issue of the ramifications of breaching aseptic technique for the patient. It was suggested by more than one staff member that the simulator could deliver a message regarding patient outcome depending on whether the wound ended up contaminated or not. An example given was:

> *'Mrs Jones just got an infection in her total hip replacement which means three months of hospitalisation, antibiotics, ... potentially she might need to have her joint replacement removed, reducing her mobility.'*

Finally, there exists the possibility of adding a gamification element to the simulation to increase engagement. Users could be scored on how sterile they kept everything, or how quickly they complete the procedure while maintaining asepsis. Perhaps, in line with current trends in popular culture, infection of the simulated patient could result in the patient becoming a zombie.

In conclusion, this research has demonstrated that utilising AR to simulate a sterile environment is both a promising and novel approach to teaching aseptic technique, a critical skill for healthcare workers in the global fight against hospital-acquired infections (HAIs). The research has also revealed several areas warranting further work.

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Appendix A: Questionnaire Design

The following is a copy of the questionnaire as used in the evaluation study.

Participant Code: _____

Gender (circle): M F

Age (circle): Under 30 30-39 40-49 50-59 60+

Relevant qualifications/training: _____

_____

Where trained? _____

_____

Work experience: _____

_____

Teaching experience: _____

_____

Experience with technology generally (Computers, iPads, Internet etc):

_____

_____

Experience with Augmented Reality technology:

_____

_____

A. The Tracking System

1. I consider that my aseptic technique in completing the task was excellent.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

2. The system perceived my aseptic technique to be excellent.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Why do you think these were the same/different?

_____

_____

3. There was no noticeable delay between physically moving objects and the system displaying those movements.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

4. The system always accurately detected when contamination occurred.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

5. The system sometimes thought something became contaminated when it actually didn't.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Do you have any suggestions about what is being detected/not detected?

_____

_____

6. The graphics displayed on the virtual mirror helped me easily identify which objects were sterile and which were contaminated.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

7. The graphics displayed on the virtual mirror were effective in alerting me to *when* contamination occurred.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

8. The sound effects were effective in alerting me to when contamination occurred.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Do you have any suggestions on how to improve the feedback from the mirror and audio?

_____

9. The tracking markers did not physically interfere with the task at hand.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

10. The tracking markers prevented me from manipulating items freely.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Any comments or suggestions for where the markers could be better placed?

_____

_____

11. The delay between my movements and what appeared on the screen was distracting.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

12. The system helped me feel aware of which items were sterile and which were not.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Why? How could this be improved?

_____

13. The system accurately assessed my aseptic technique.

Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

Why? How could this be improved?

_____

_____

B. Training Potential

For these questions, consider a future augmented reality system that has flawless tracking.

1. An augmented reality system like this has great training potential in the area of aseptic technique.

   Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

   Comments:

   _____

2. A system like this would be effective in helping students *understand the concept* of a sterile field.

   Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

   Comments:

   _____

3. A system like this would be effective in *communicating the importance* of maintaining a sterile field.

   Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

   Comments:

   _____

4. A system like this would be effective in helping students to develop an aseptic conscience
   (ie. an awareness of which items are sterile and non sterile).

   Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

   Comments:

   _____

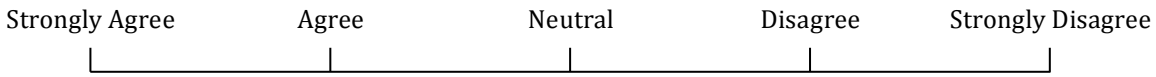
5. Assuming I had access to a system like this, I would be likely to use it for teaching aseptic technique in the classroom.

   Strongly Agree | Agree | Neutral | Disagree | Strongly Disagree

   Why?

   _____

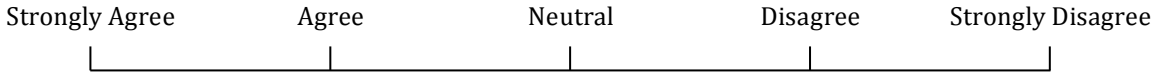
6. Better tracking performance would be required before this became a useful teaching tool.



Comments:

_____

7. The system would have to work without the need for tracking markers attached to everything before this became a useful teaching tool.



Comments:

_____

_____

C. Open Ended Questions

1. What do you like about the system?

_____

_____

2. What do you dislike about the system?

_____

_____

3. Can you see a system like this being used to help teach aseptic technique in the classroom? Explain.

_____

_____

4. What needs improvement in order for it to be used in the classroom?

_____

_____

5. What aspects of aseptic technique do you think this system is able to teach?

_____

_____

6. What aspects of aseptic technique do you think this system is unable to teach?

   _____

   _____

7. How well do you think a system such as this would be able to communicate aseptic technique errors to students?

   _____

   _____

8. In what ways does the system fall short of effectively teaching aseptic technique?

   _____

   _____

9. What specific benefits do you see in using augmented reality technology for this type of training over a more traditional mouse-and-keyboard or touch-screen approach?

   _____

   _____

   _____

10. Any other comments or suggestions?

    _____

    _____

    _____

Appendix B: Questionnaire Responses

Questionnaire responses are included on the accompanying CD-ROM.

Appendix C: Data Analysis Spreadsheet

A spreadsheet containing data analysis is included on the accompanying CD-ROM.

Appendix D: ARSterileSim Unity Scripts

Key scripts from ARSterileSim are included on the accompanying CD-ROM.